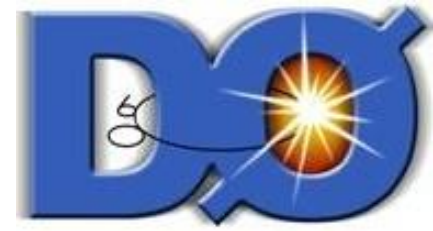




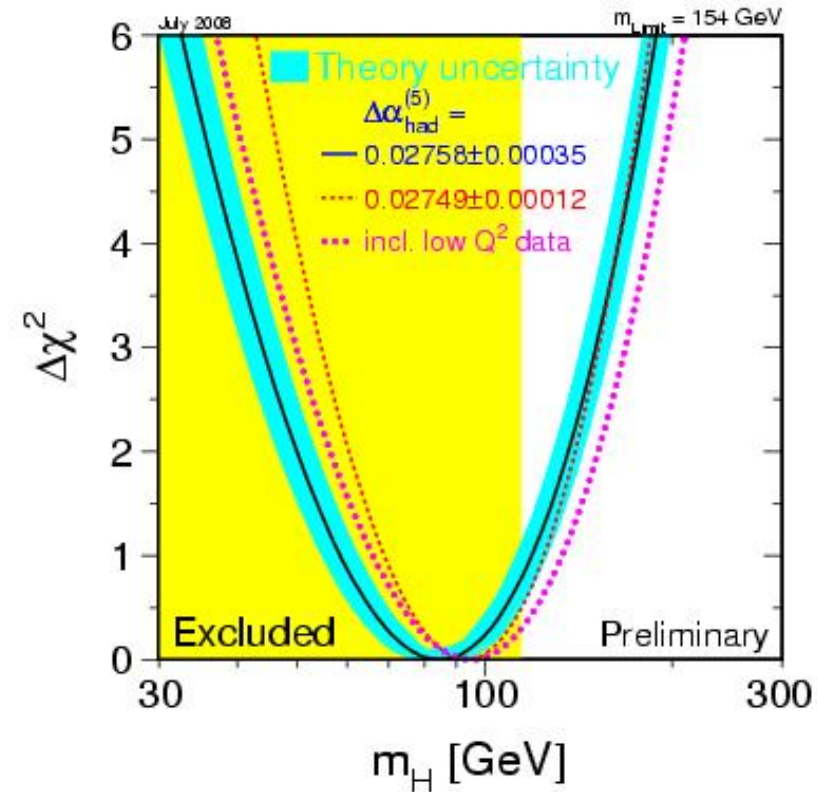
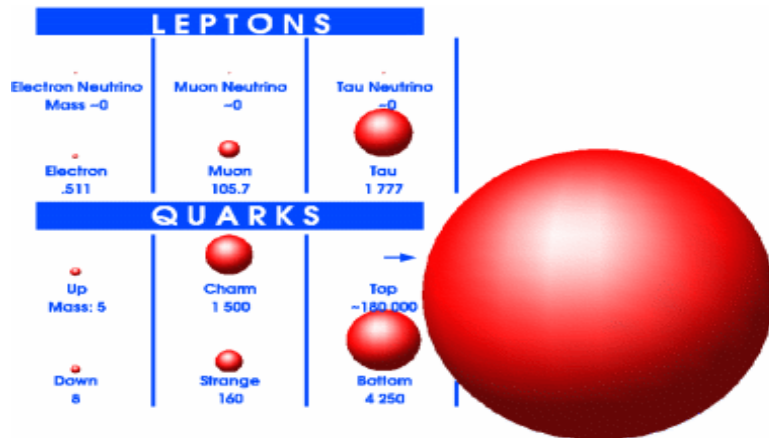
Top Quark Measurements at the Tevatron

Zhenyu Ye / Fermilab
for CDF and DØ Collaborations



Why is Top Interesting?

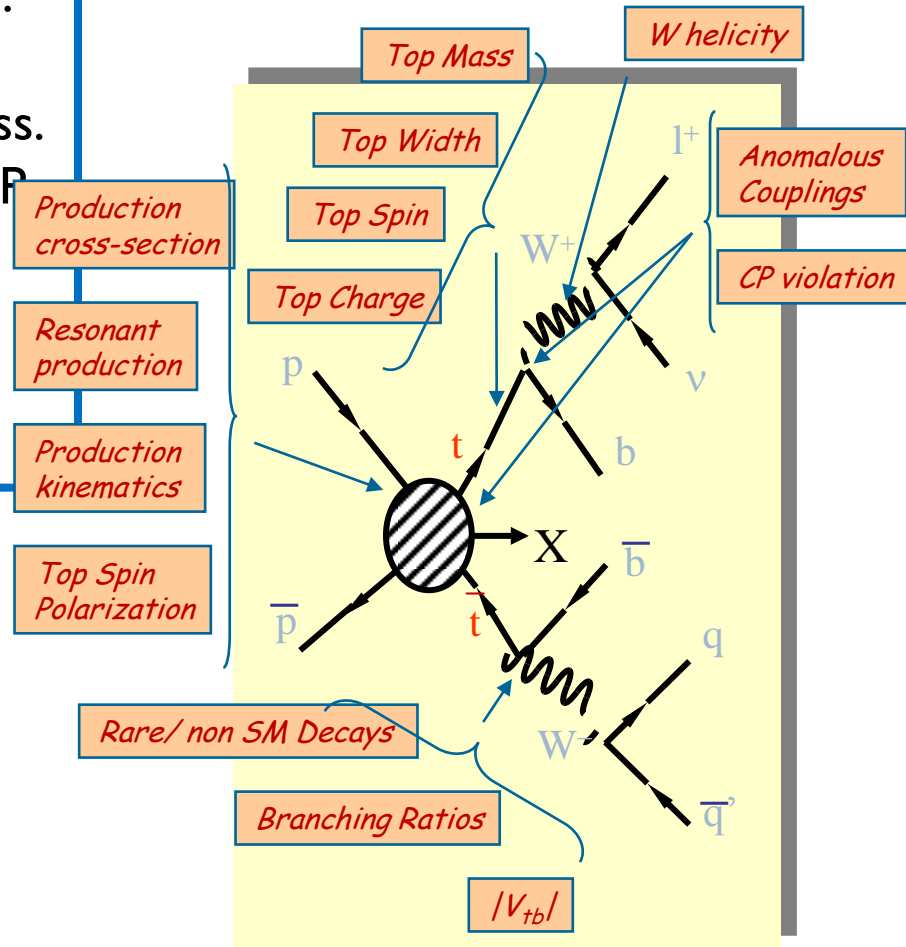
- Discovered by CDF and DØ in 1995.
- Pair production by strong interaction. EW decay and single production.
- Top+W mass constrain SM Higgs mass.
- A major background for Higgs and NP searches.
- Most of the interests come from the potential to find NP, e.g., why is it so heavy? Is it the SM top? ...



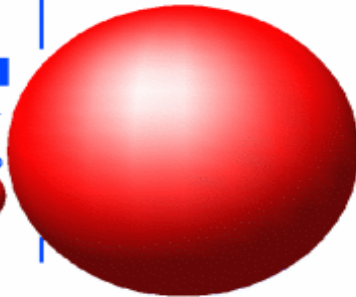
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Very Rich Physics Program



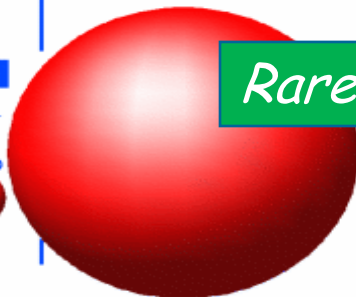
| LEPTONS | | |
|------------------------------------|---------------------------|--------------------------|
| Electron Neutrino Mass ~ 0 | Muon Neutrino ~ 0 | Tau Neutrino ~ 0 |
| Electron 0.511 | Muon 105.7 | Tau 1.777 |
| QUARKS | | |
| Up Mass: 5 | Charm 1.500 | Top $\sim 180,000$ |
| Down 5 | Strange 160 | Bottom 4.250 |



Why is Top Interesting?

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- Pair production by strong interaction. EW decay and single production
- Top+W mass constrain SM Higgs
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| LEPTONS | | |
|------------------------------|---------------------|--------------------|
| Electron Neutrino Mass ~0 | Muon Neutrino ~0 | Tau Neutrino ~0 |
| Electron .511 | Muon 105.7 | Tau 1 777 |
| QUARKS | | |
| Up Mass: 5 | Charm 1 500 | Top ~180 000 |
| Down 8 | Strange 160 | Bottom 4 250 |



Production cross-section

Resonant production

Production kinematics

Top Spin Polarization

Rare/ non SM Decays

Branching Ratios

$|V_{tb}|$

Presented Results

Top Mass

W helicity

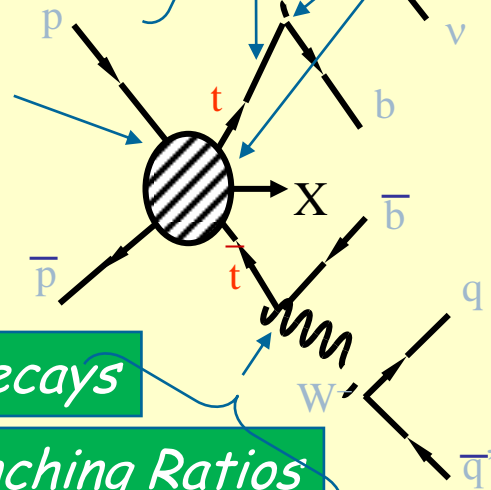
Anomalous Couplings

CP violation

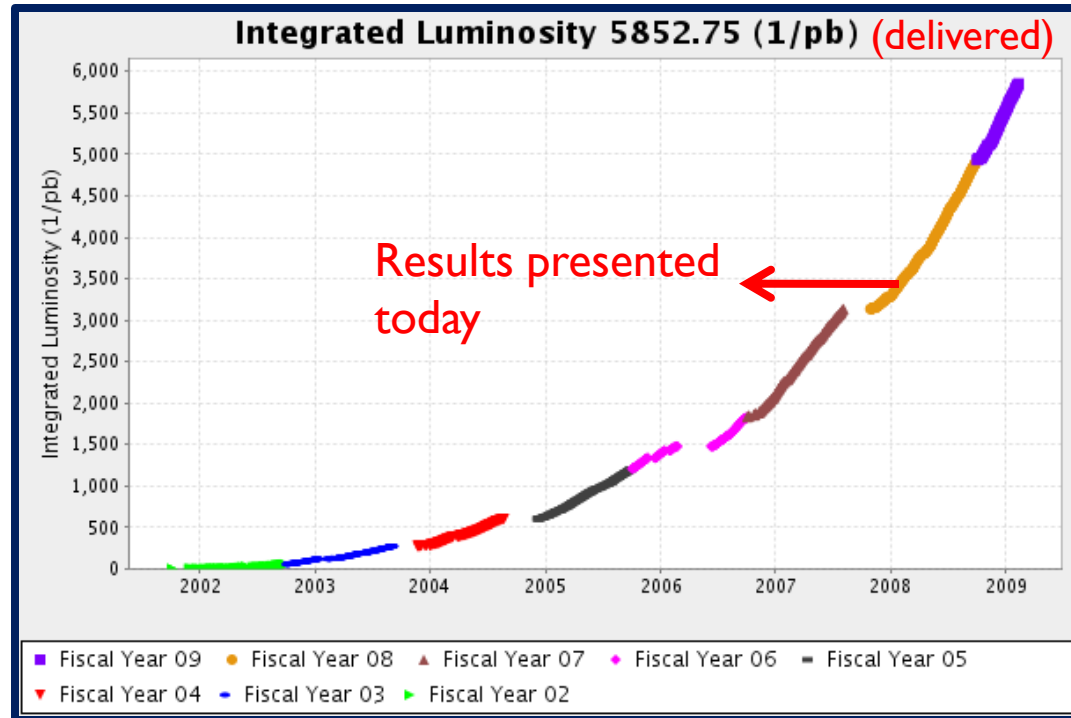
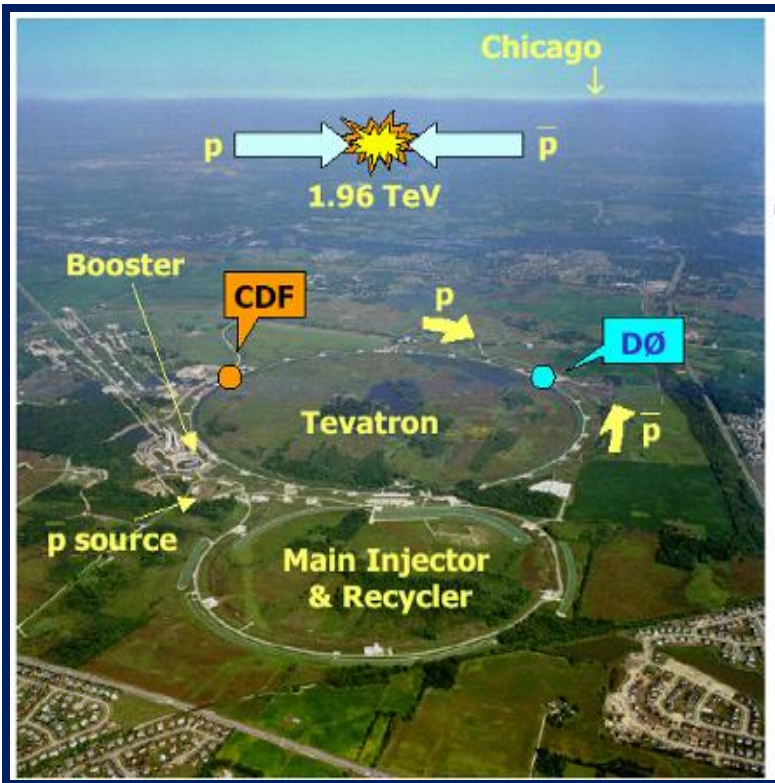
Top Width

Top Spin

Top Charge



Tevatron At Fermilab



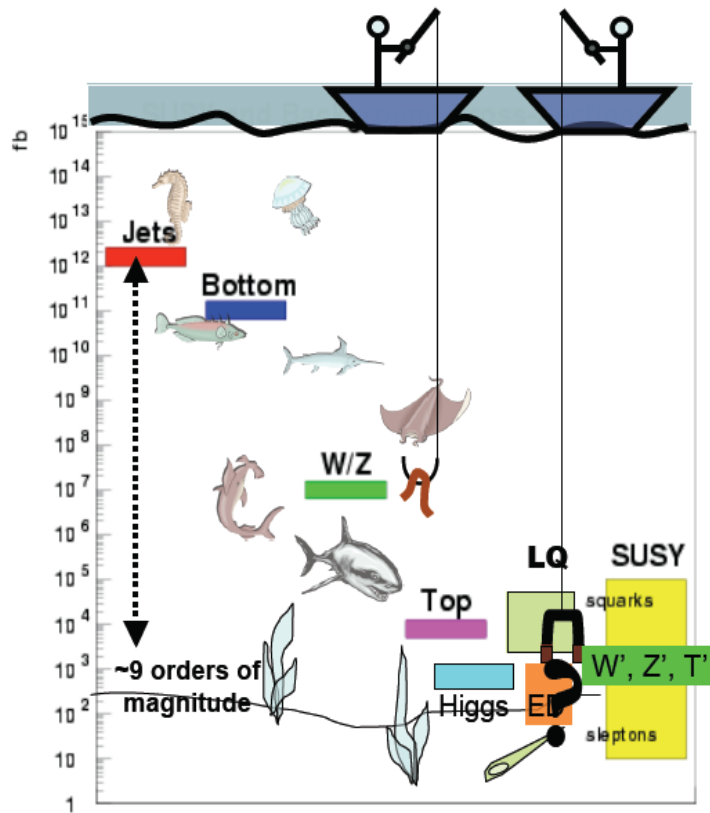
The only place that has produced top quarks!

Excellent performance:

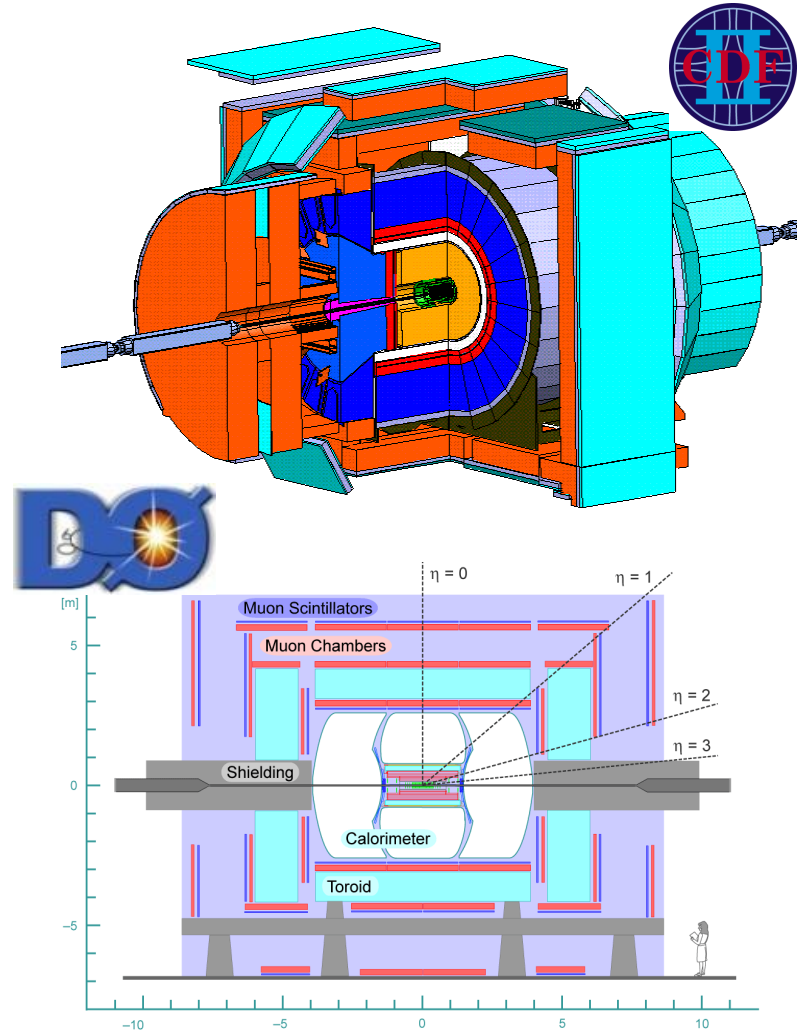
- Record instantaneous lumi.: $3.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Total delivered $\sim 5.8 \text{ fb}^{-1}$
- Results based on $< 3.5 \text{ fb}^{-1}$
- Projected $\sim 10 \text{ fb}^{-1}$ by end of FY10

CDF and Dzero Detectors

PRODUCTION CROSS SECTION

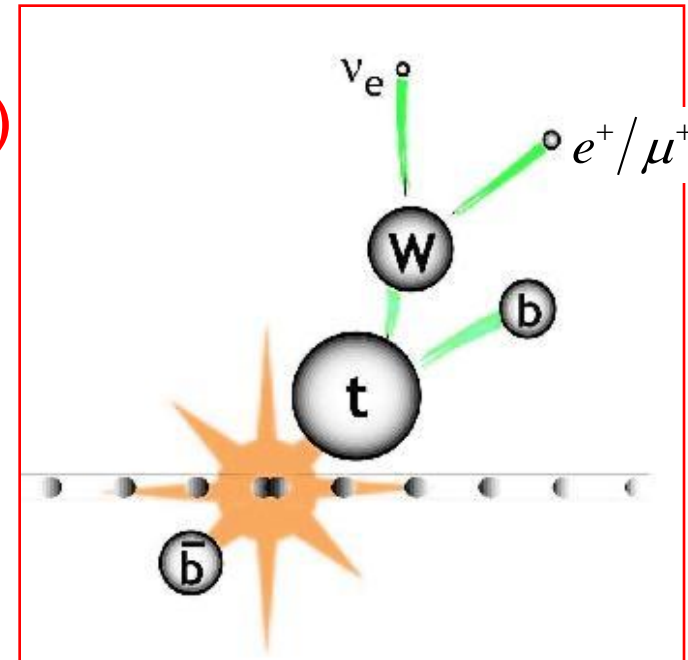


Finding Top quarks is challenging!



Selected Results

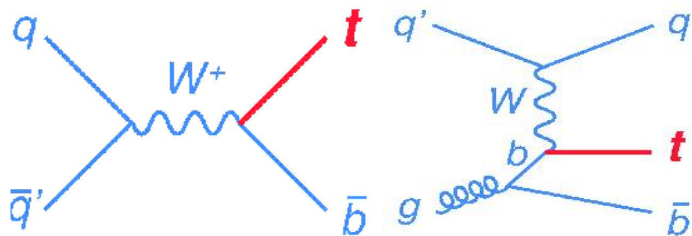
- ▶ **Single top production**
 - cross section ($|V_{tb}|$, anomalous coupling)
- ▶ **Top pair production**
 - cross section, $M(t\bar{t})$ spectrum
 - search for new physics ($t\bar{t}H$, t')
- ▶ **Top decay**
 - branching ratio, FCNC, rare decay
 - charged Higgs search
 - W -helicity
- ▶ **Top mass**



Single Top Production

At the Tevatron:

s-channel: 0.88 pb t-channel: 1.98 pb



Direct access to the Wtb coupling

- overall rate and ratio between s- and t-channels are sensitive to NP

- Experimental challenge:

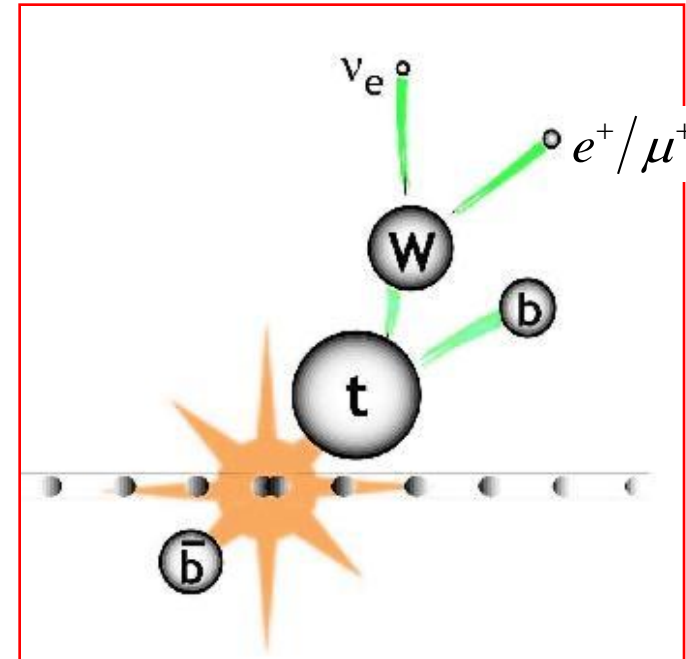
- cross section \sim half of the $t\bar{t}$

- mostly done in lep+MET+jets

- large backgrounds from W +2 jets

- $S/B \sim 1/200$ before b -tagging

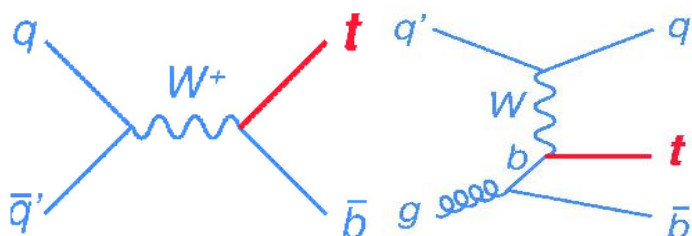
- Need multivariate techniques to extract signal.



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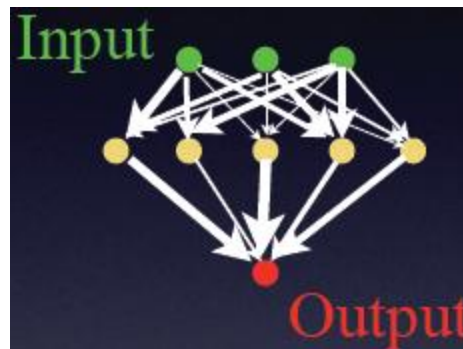
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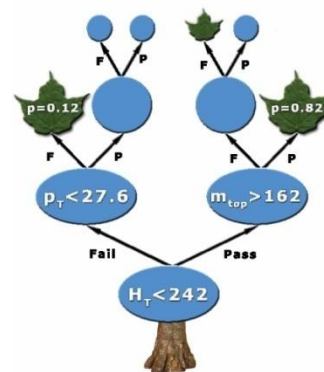
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- $S/B \sim 1/200$ before b -tagging

- Need multivariate techniques to extract signal.



Neural Network:
Train with MC to
optimize weight



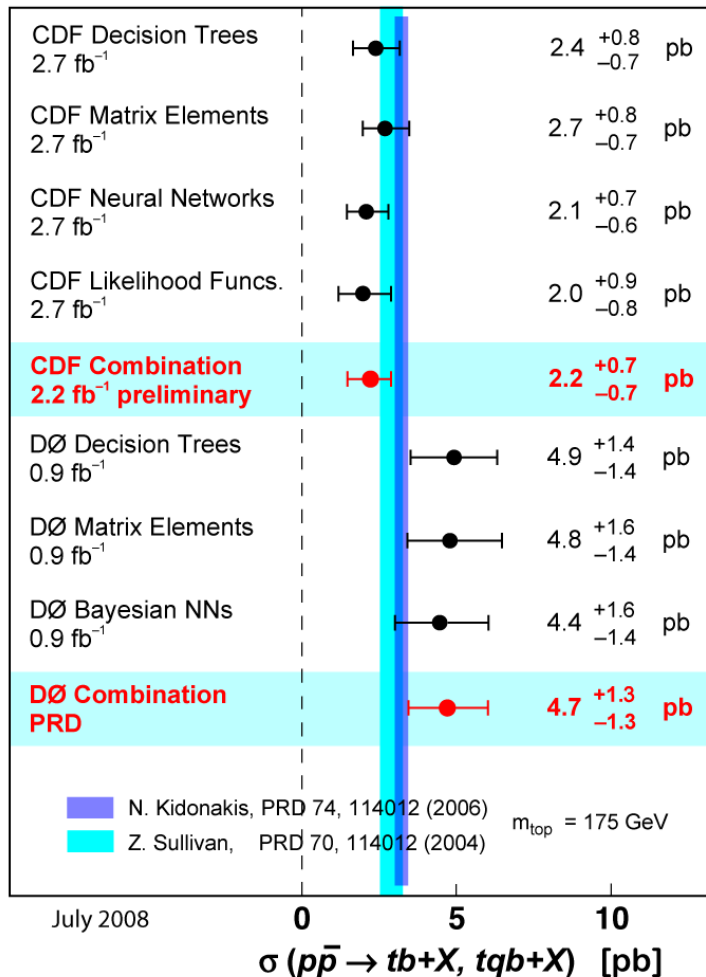
Boosted Decision Trees:
Train with MC to
determine the shape of
the tree

Matrix Element:

Calculate signal/background probabilities
from the cross section Matrix Element
and detector resolutions

Single Top Production – Cross Section, V_{tb}

CDF and DØ $tb+tbq$ Cross Section



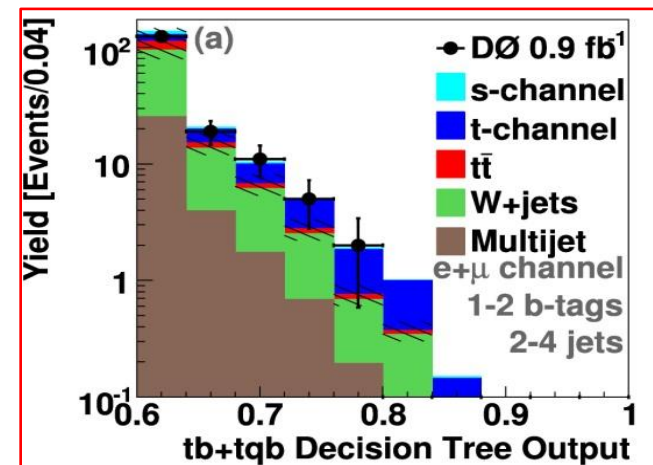
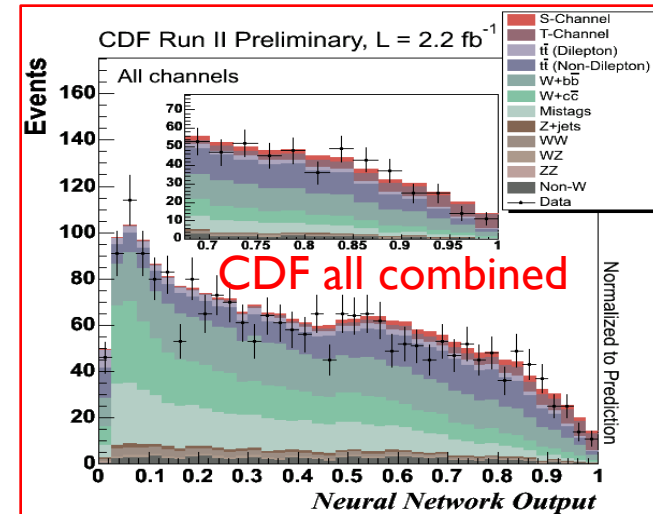
$\sigma = 2.2 \pm 0.7 \text{ pb}$

5.1 σ exp. significance
 3.7 σ obs. significance
 $0.66 < |V_{tb}| \leq 1$ at 95% C.L.



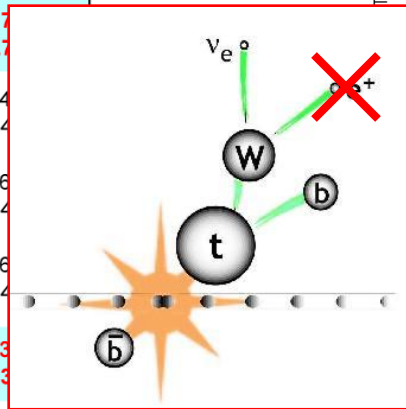
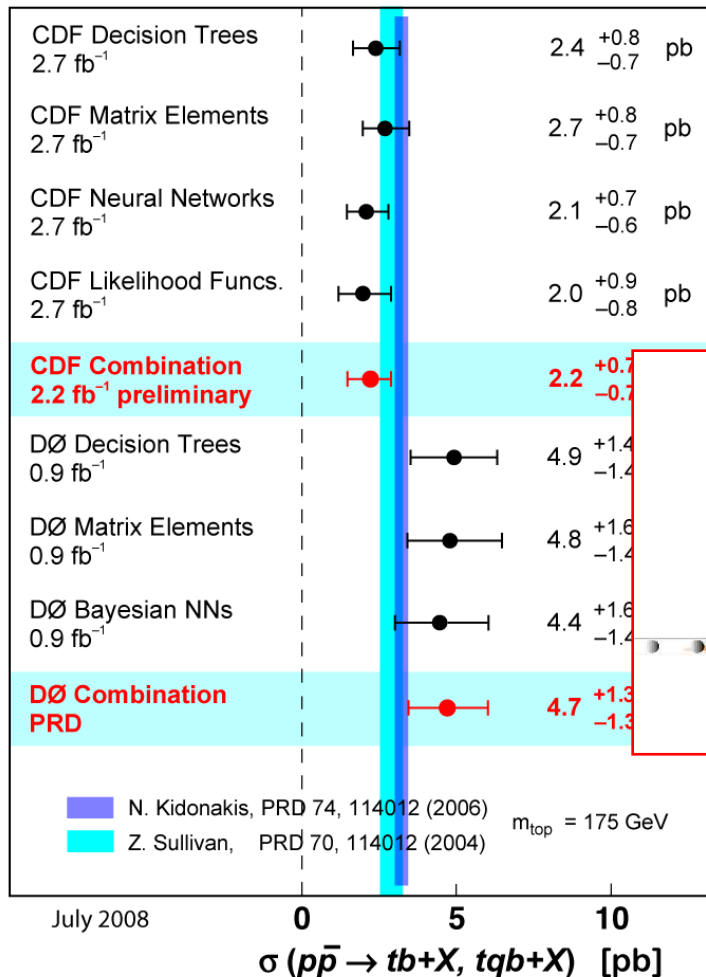
$\sigma = 4.7 \pm 1.3 \text{ pb}$

2.3 σ exp. significance
 3.6 σ obs. significance
 $0.68 < |V_{tb}| \leq 1$ at 95% C.L.

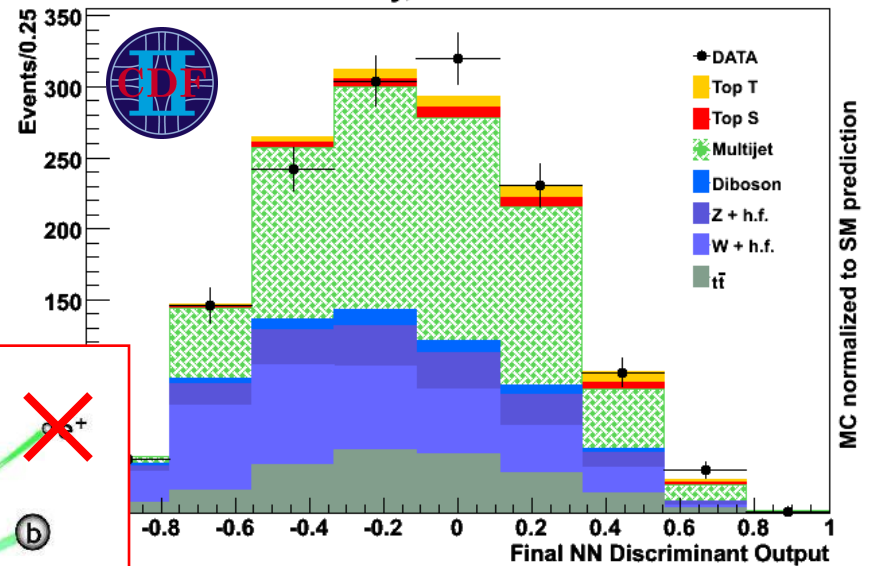


Single Top Production – Cross Section, V_{tb}

CDF and DØ $tb+tbq$ Cross Section

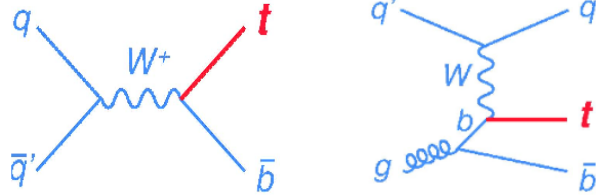


CDF Run II Preliminary, 2.1 fb⁻¹



New channel explored by CDF:
MET + jets $4.9^{+2.5}_{-2.2}$ pb
 complement the acceptance
 1.4 σ (2.1 σ) exp. (obs.) significance

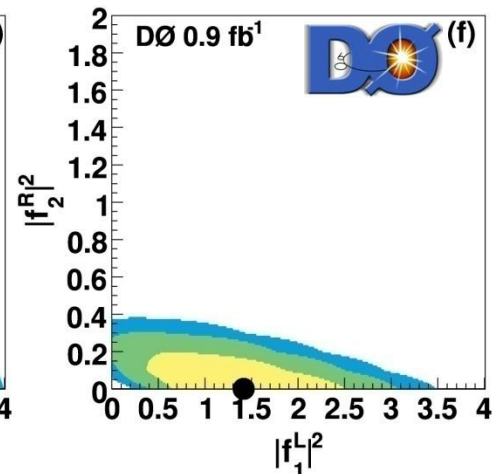
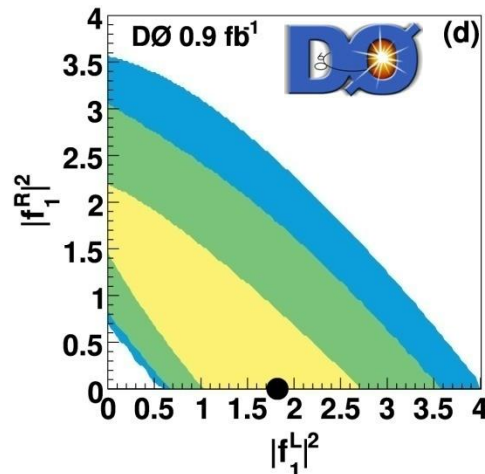
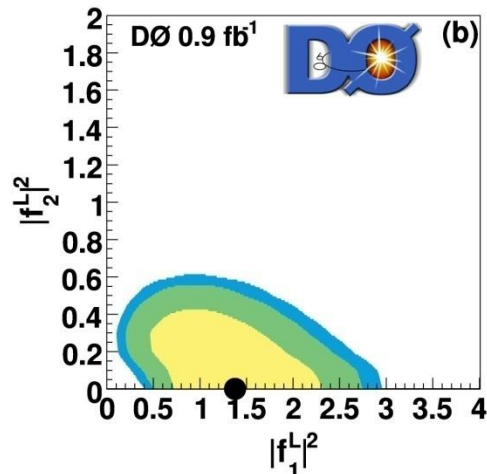
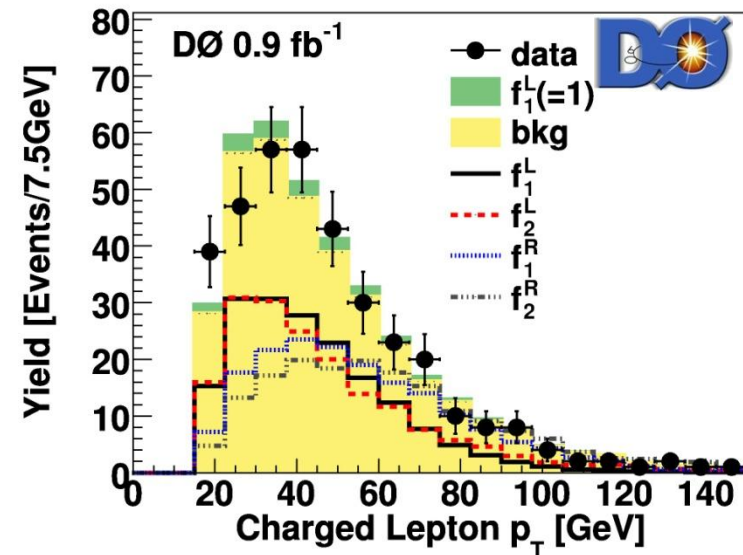
Constraints on Anomalous Couplings



$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t$$

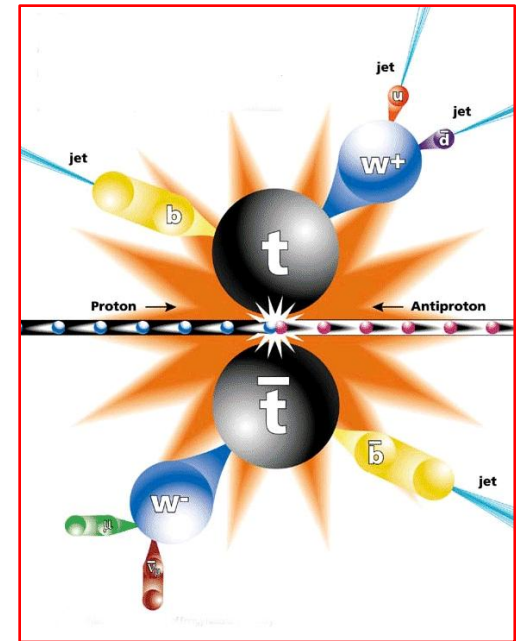
$$- \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

In SM: $f_1^L = |V_{tb}| \approx 1, f_1^R = f_2^L = f_2^R = 0$



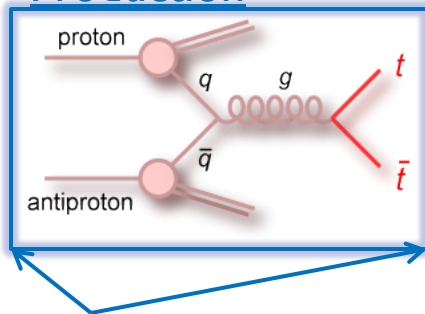
Selected Results

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 - search, cross section ($|V_{tb}|$, anomalous coupling)
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 - W-helicity (anomalous coupling)
- ▶ Top mass

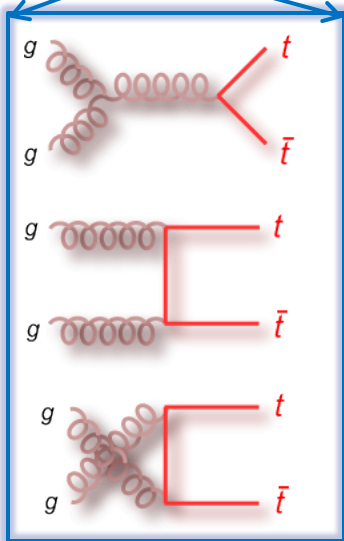


Top Pair Production

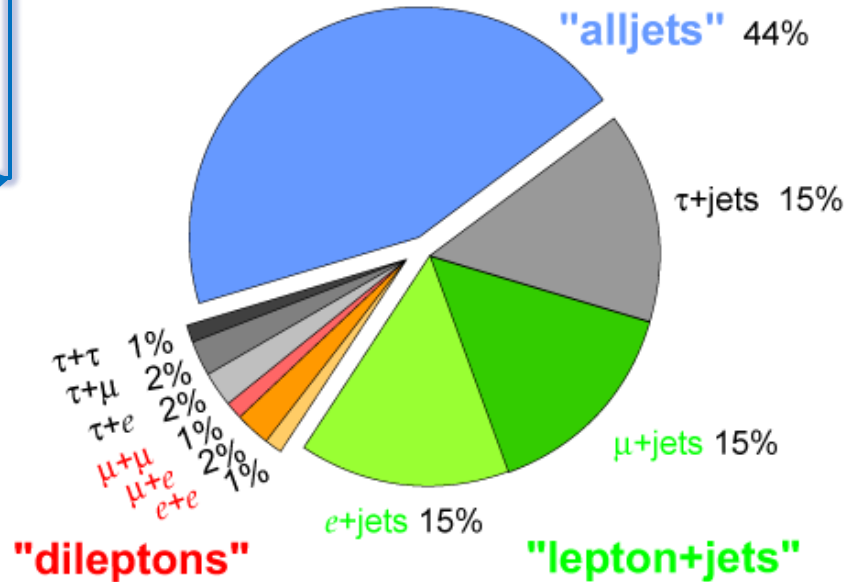
Production



~85% qqbar
~15% gg



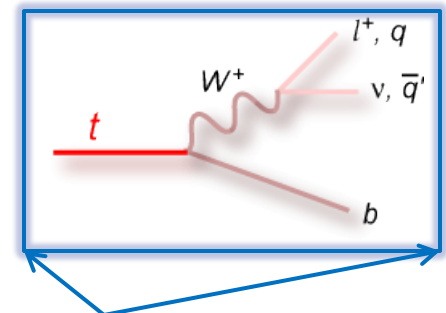
Top Pair Branching Fractions



main background:

- W/Z + jets
- multi-jets

Decay



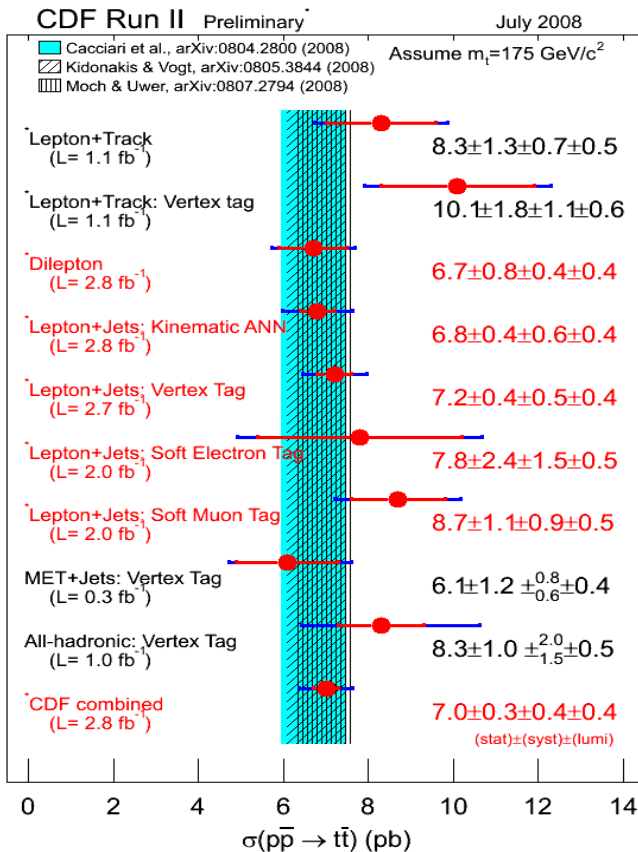
100% $t \rightarrow W+b$ in SM
 $\Gamma^{\text{SM}} \approx 1.4 \text{ GeV}$ at $m = 175 \text{ GeV}$

event selection by:

- event kinematics and topology
- isolated lepton (optional)
- MET (optional)
- b-jet ID (optional)

Top Pair Production - Cross Section

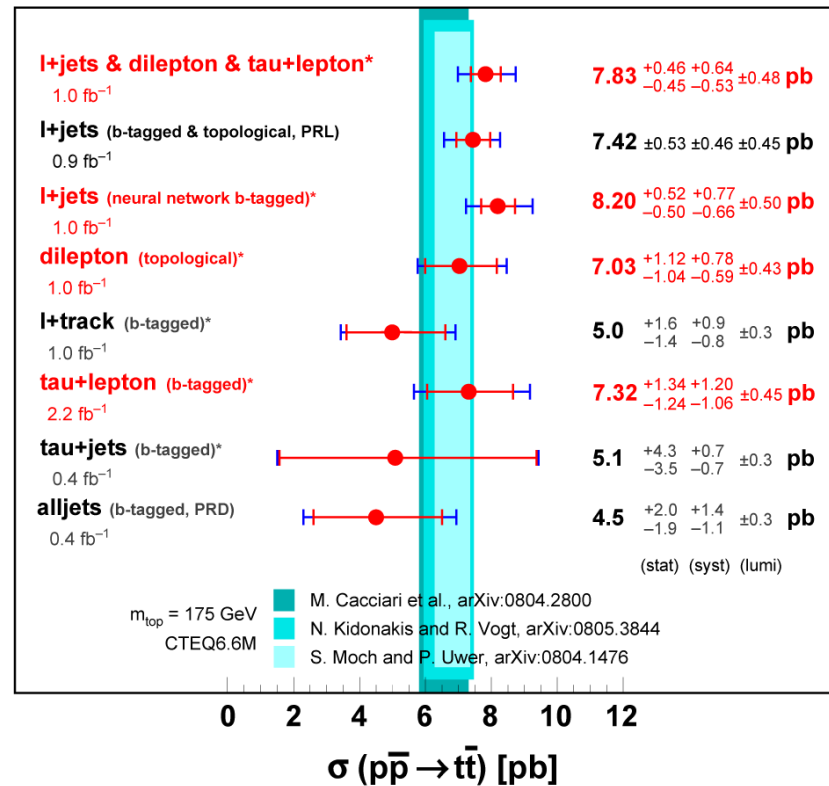
Measure in different final states. NP may affect differently.



CDF combined (0.3-2.8 fb⁻¹) :
7.0 ± 0.3(stat) ± 0.4(syst) ± 0.4(lumi) pb

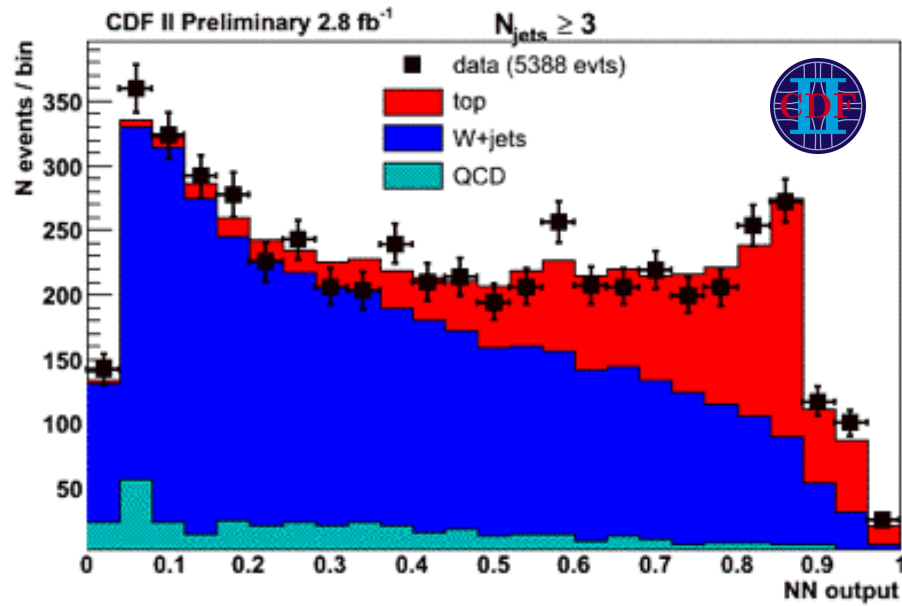
DØ Run II * = preliminary

August 2008



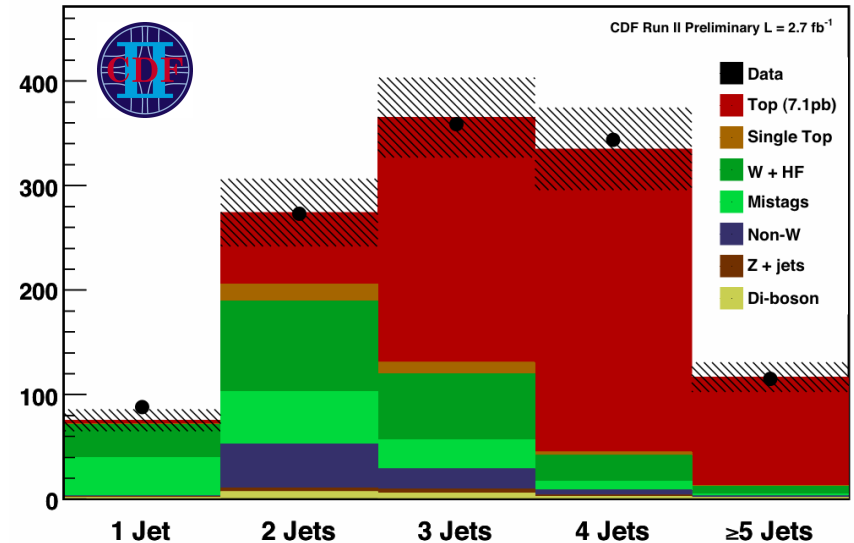
DØ combined (0.4-2.2 fb⁻¹):
7.8 ± 0.5(stat) ± 0.6(syst) ± 0.5(lumi) pb

Top Cross Section - Top/Z Ratio



CDF NN (2.8 fb⁻¹):

$6.9 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.1(\text{theo})$ pb



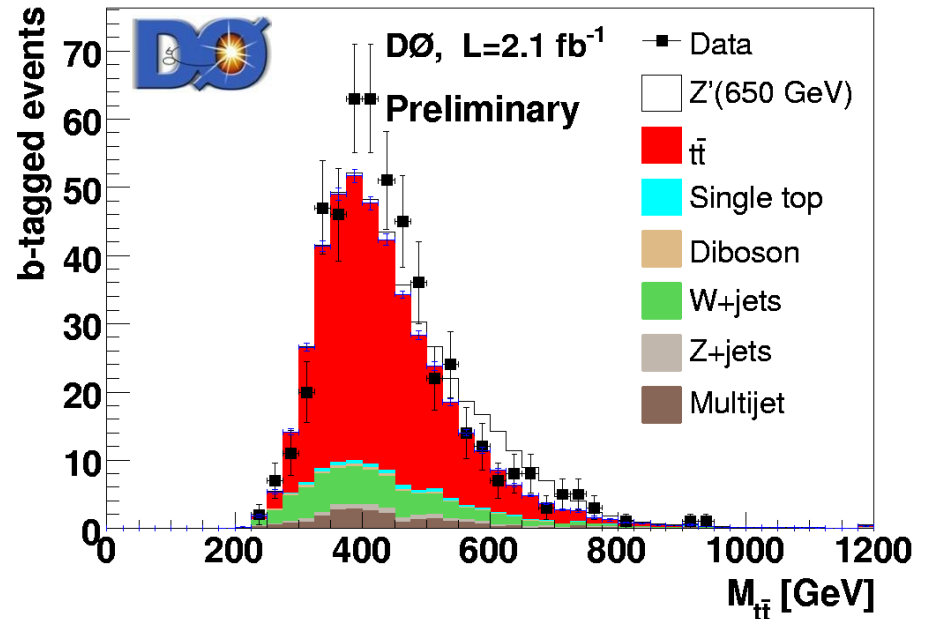
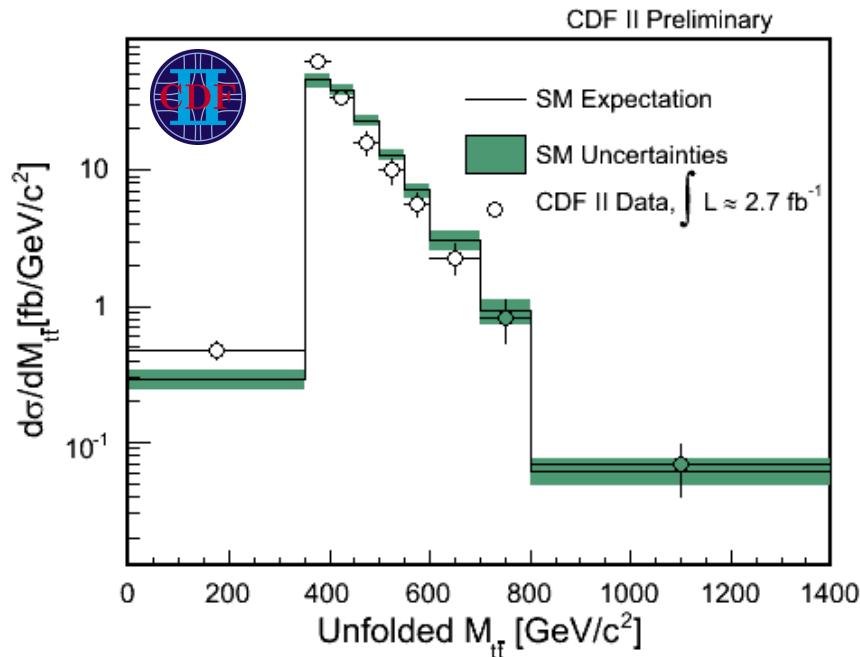
CDF btagged (2.8 fb⁻¹):

$7.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{theo})$ pb

CDF recently measured the Top cross section through Top/Z ratio with greatly reduced systematic uncertainty due to lumi.

The uncertainty in one single measurement is 8.2% (9.7% in direct measurement), comparable to theoretical uncertainty.

M(ttbar) Diff. Cross Section/Spectrum



in Randall-Sandrum model

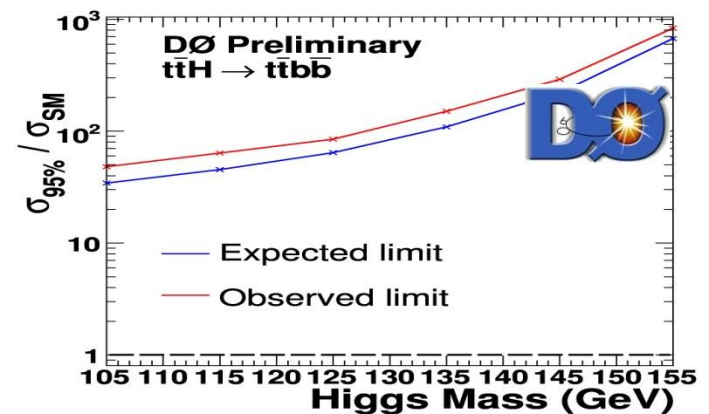
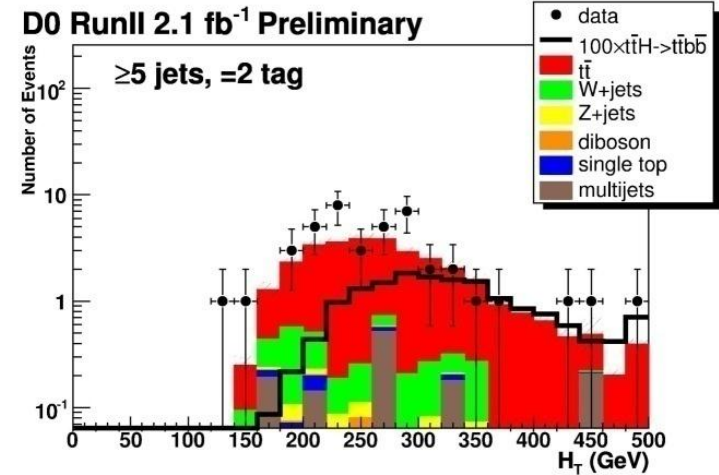
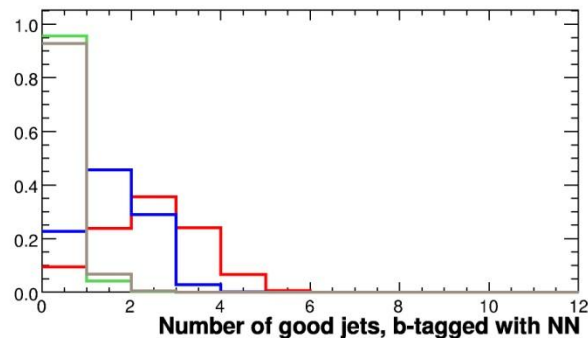
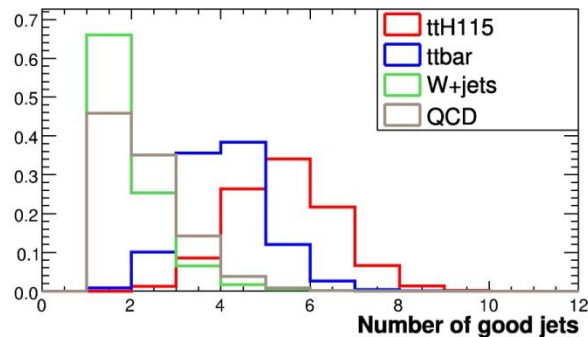
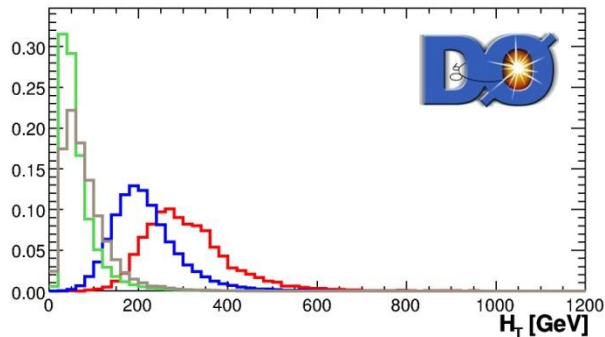
$$\kappa/M^{Pl} > 0.16 @ 95\% CL$$

$$m_{Z'} > 760 \text{ GeV} @ 95\% CL$$



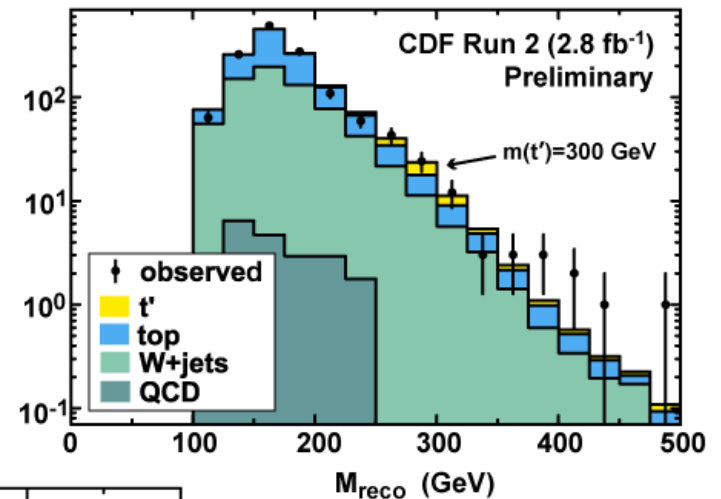
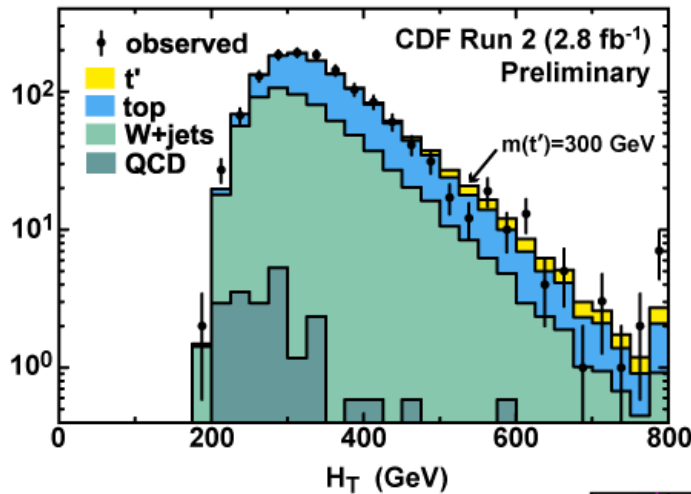
M(tt) sensitive to a broad class of NP models, e.g. peak-dip structure (MSSM), narrow resonances (Z' boson). No evidence for new physics.

Search for New Physics – $ttH(->b\bar{b})$

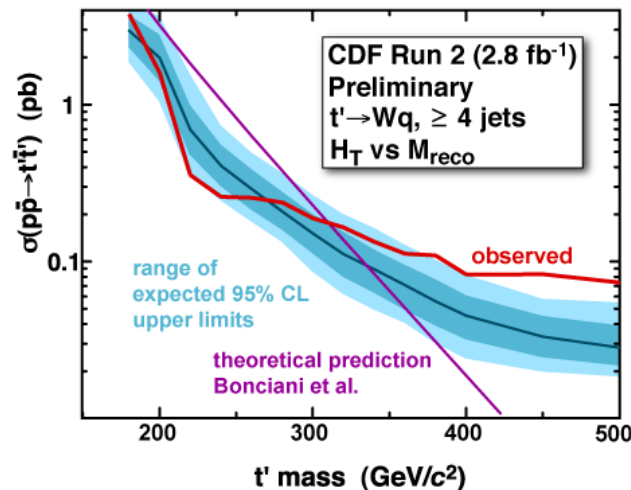


$\sigma(ttH) < 64 \times \text{SM value}$
for $M_{Higgs} = 115 \text{ GeV}$

Search for New Physics – t'



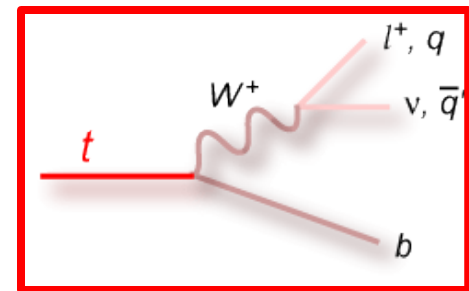
Assuming t'
pair-produced strongly
mass larger than top
decay promptly to Wq



$$m_{t'} > 311 \text{ GeV @ 95\% CL}$$

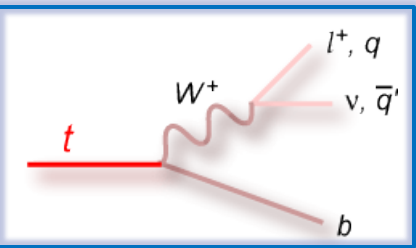
Selected Results

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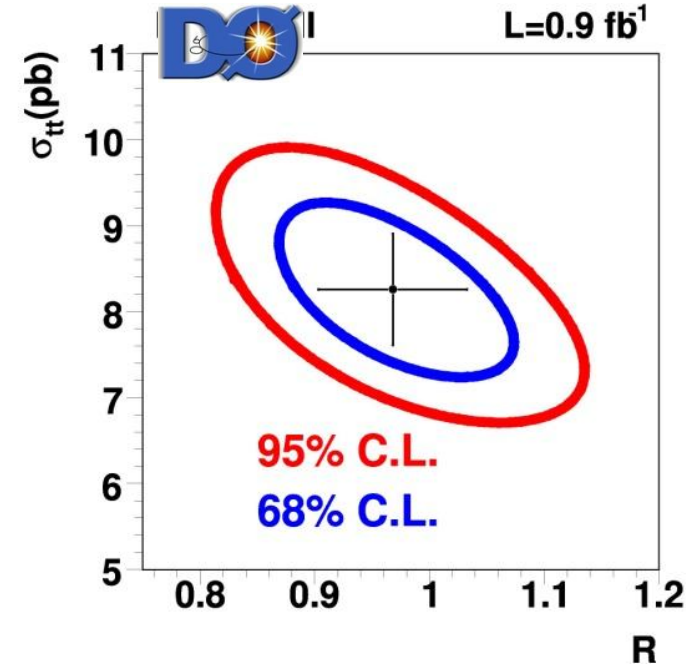
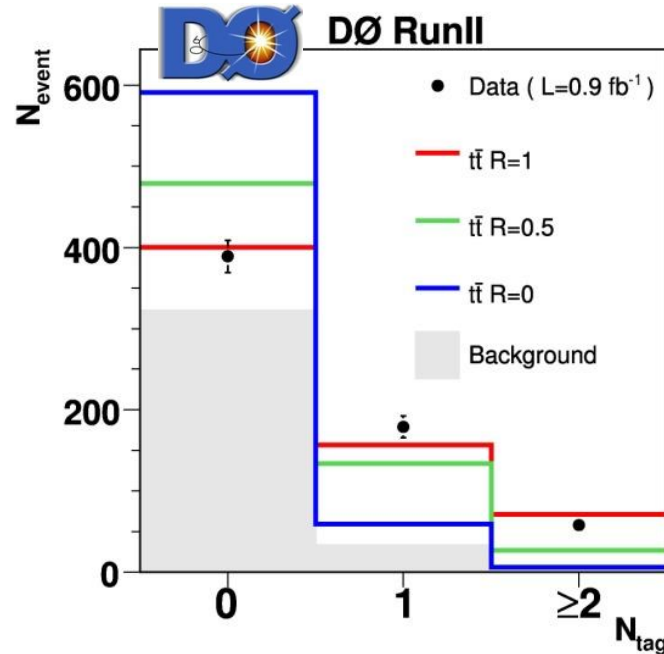


Top Decay - Branching Ratio

Decay



100% $t \rightarrow W+b$ in SM,
deviations suggest NP

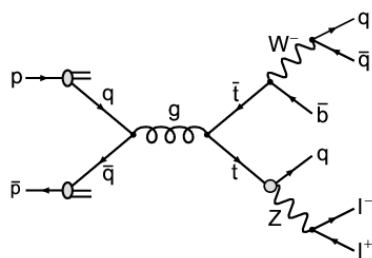


$$R = \text{Br}(t \rightarrow Wb) / \text{Br}(t \rightarrow Wq) \\ > 0.79 \text{ @95\% C.L.}$$

$$|V_{tb}| > 0.89 \text{ @95\% C.L. (if 3x3 CKM is unitary)}$$

Top Decay – FCNC, Invisible Decay

SM FCNC branching ratio $\sim 10^{-14}$



Sensitive to NP



$$B(t \rightarrow Zq) < 3.7\% \text{ @ } 95\% \text{ C.L.}$$

Invisible Decay Search:

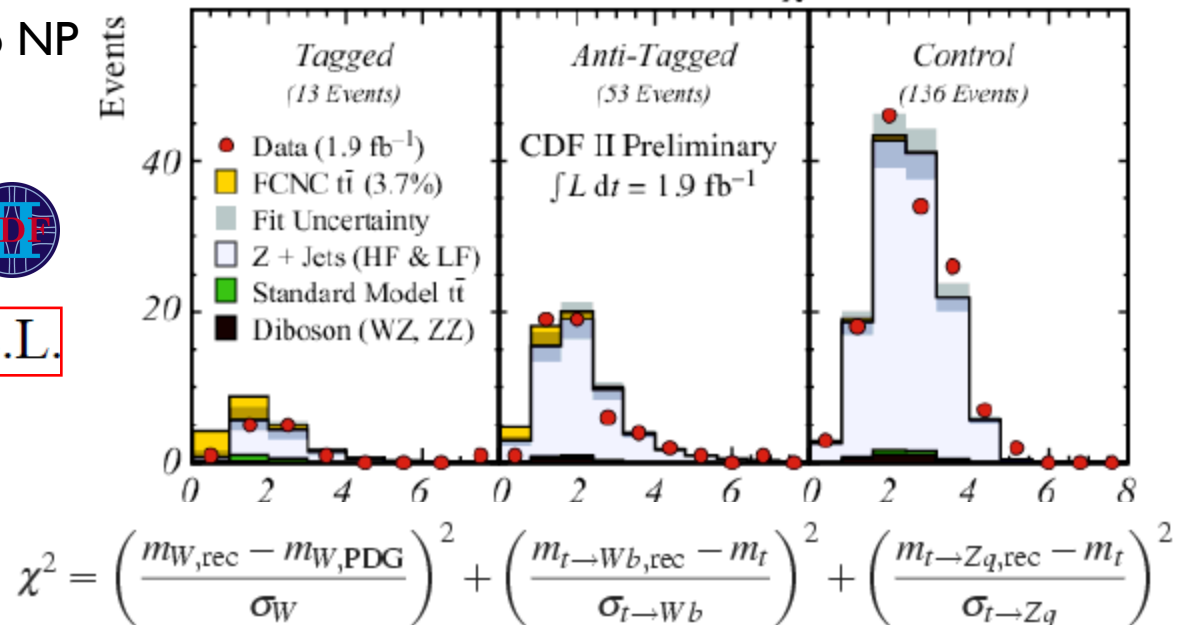
Measure absolute rate of events with 2 btag-jets to determine $\text{Br}(t \rightarrow X)$. X is a state with different acceptance than Wb



$$B(t \rightarrow Zc) < 13\%$$

$$B(t \rightarrow \text{invisible}) < 9\%$$

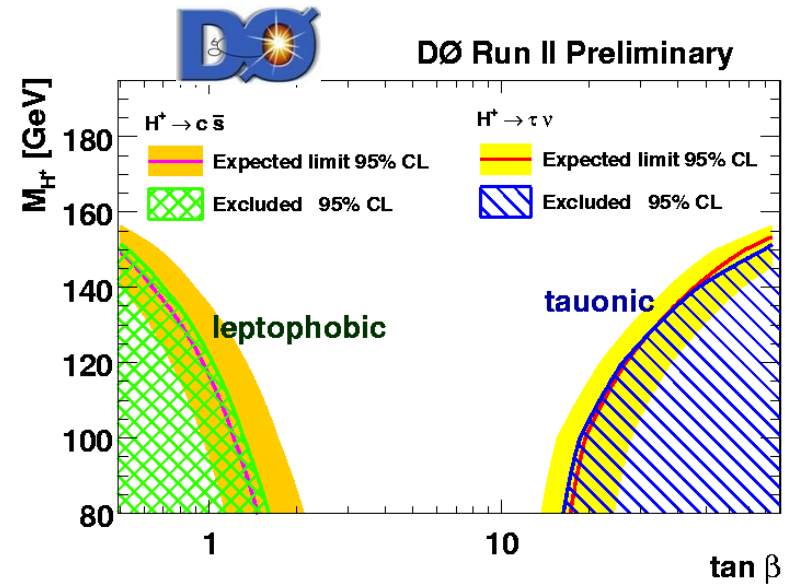
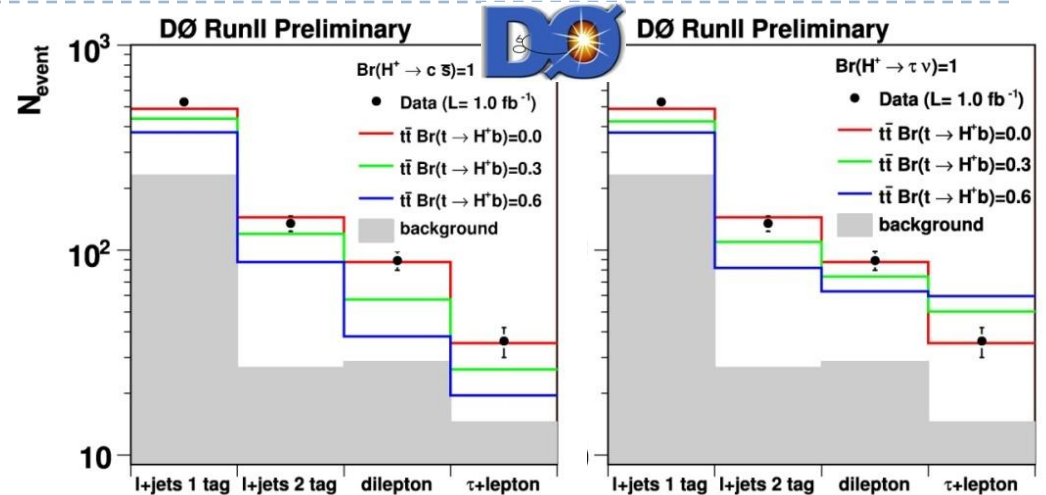
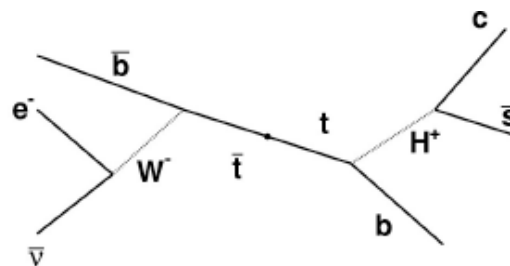
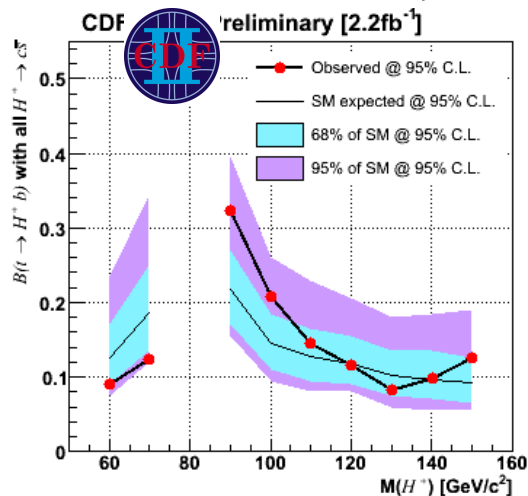
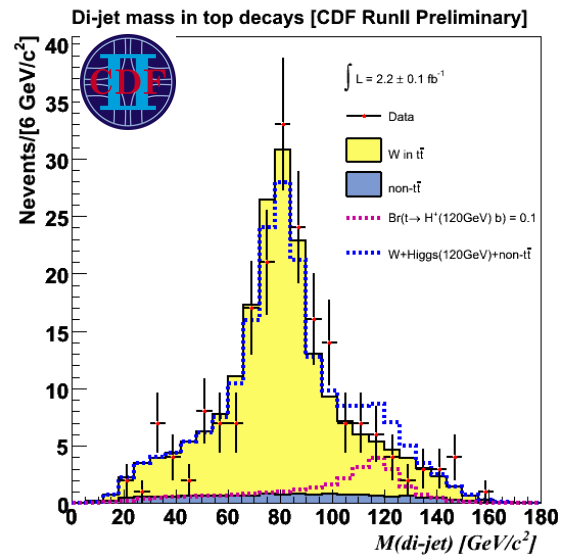
Best Fit to Mass χ^2



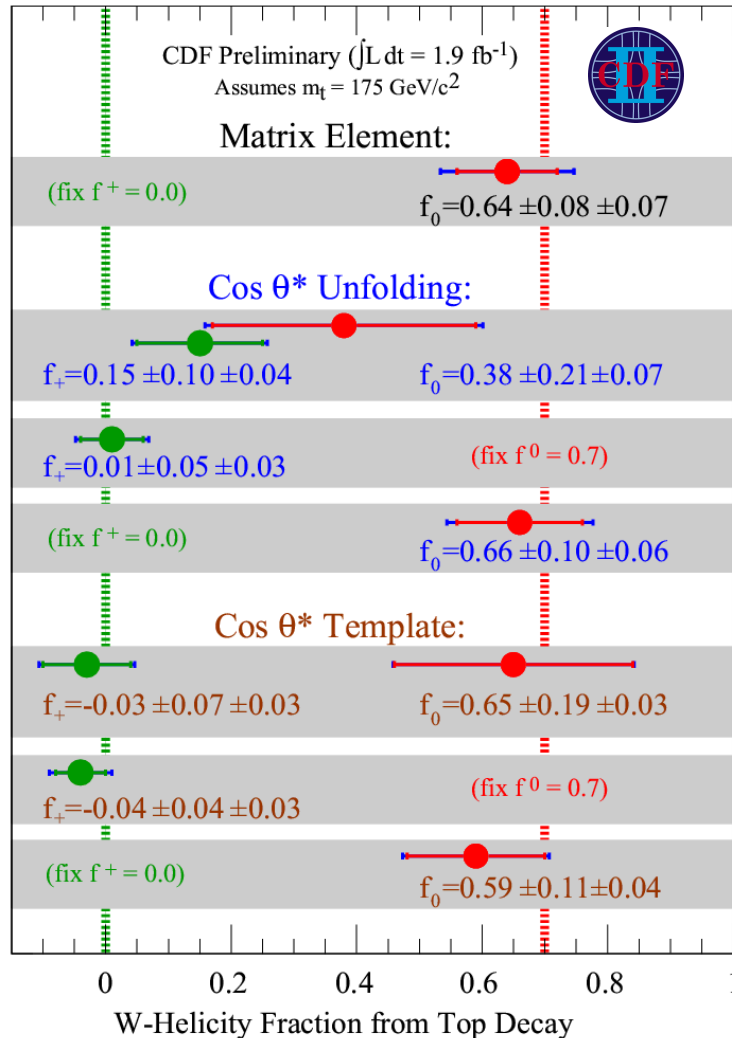
CDF Run II Preliminary 1.9 fb^{-1}

| Decay | $\mathcal{B}_{Wb/Wb}$ (%) | Upper Limit (%) (175 GeV) | Upper Limit (%) (172.5 GeV) | Upper Limit (%) (170 GeV) |
|---|---------------------------|------------------------------|--------------------------------|------------------------------|
| $\mathcal{B}(t \rightarrow Zc)$ | 32 | 13 | 15 | 18 |
| $\mathcal{B}(t \rightarrow gc)$ | 27 | 12 | 14 | 17 |
| $\mathcal{B}(t \rightarrow \gamma c)$ | 18 | 11 | 12 | 15 |
| $\mathcal{B}(t \rightarrow \text{invisible})$ | 0 | 9 | 10 | 12 |

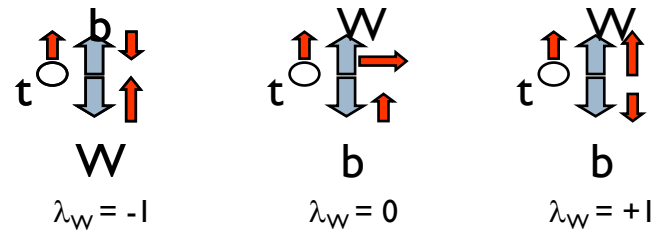
Top Decay – H^+ ($m_{H^+} < m_t$) Search



Top Decay - W-Helicity

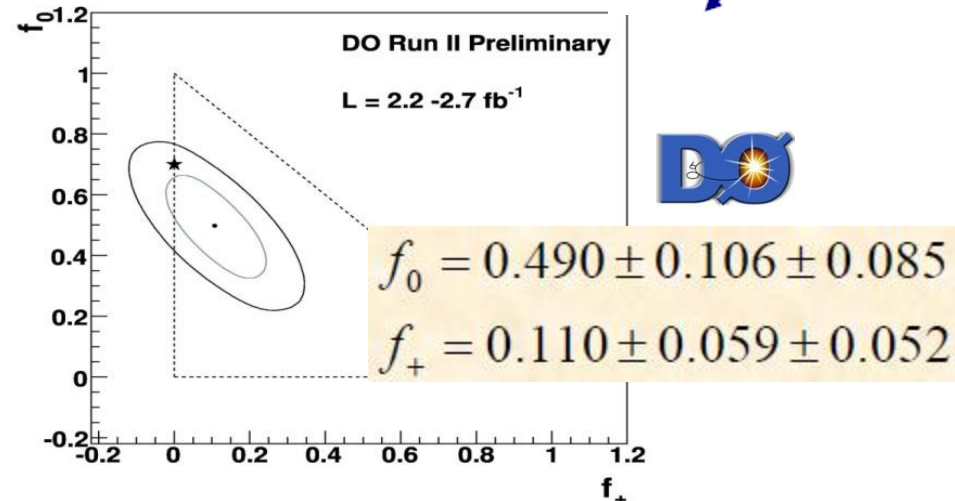
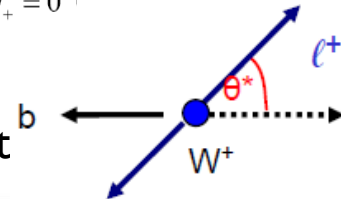


W helicity in top quark decays



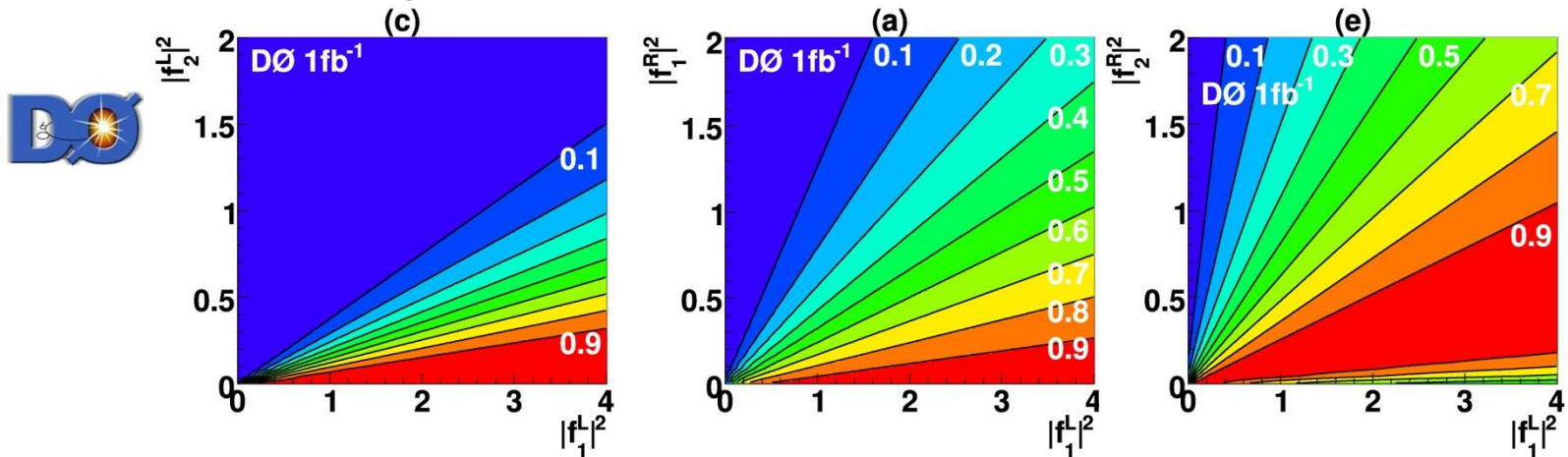
$$F_- \approx \frac{2M_W^2}{m_t^2 + 2M_W^2} = 0.30 \quad F_0 \approx \frac{m_t^2}{m_t^2 + 2M_W^2} = 0.70 \quad F_+ = 0$$

- Reconstruct helicity angle of lepton in top quark pair event

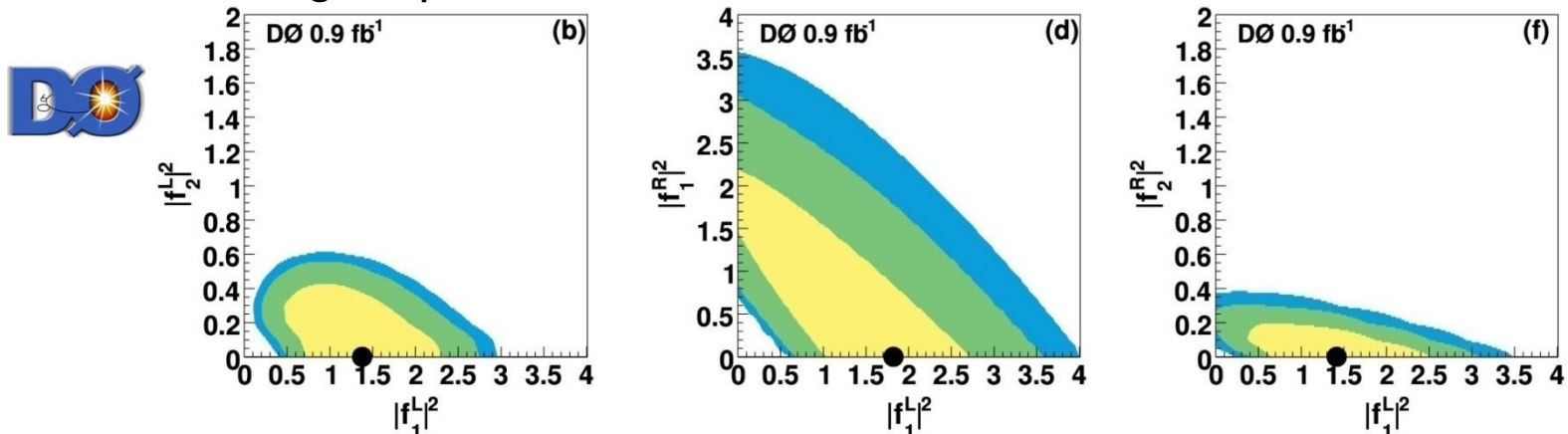


Constraints on Anomalous Couplings

Constraint from VV-helicity

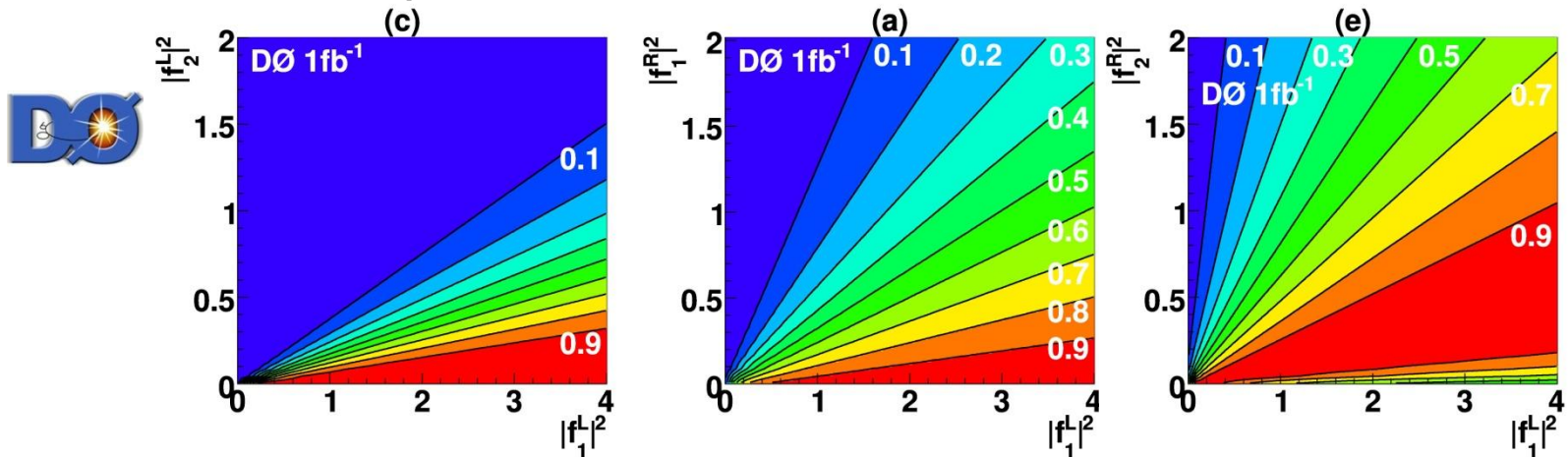


Constraint from single top

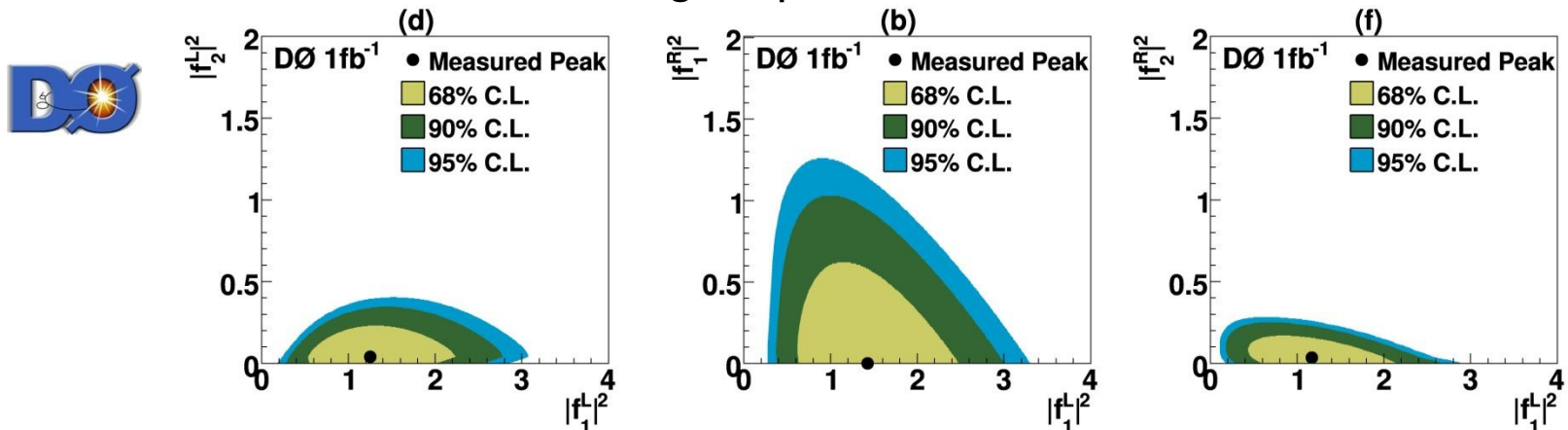


Constraints on Anomalous Couplings

Constraint from VV-helicity



Combined with the constraint from single top

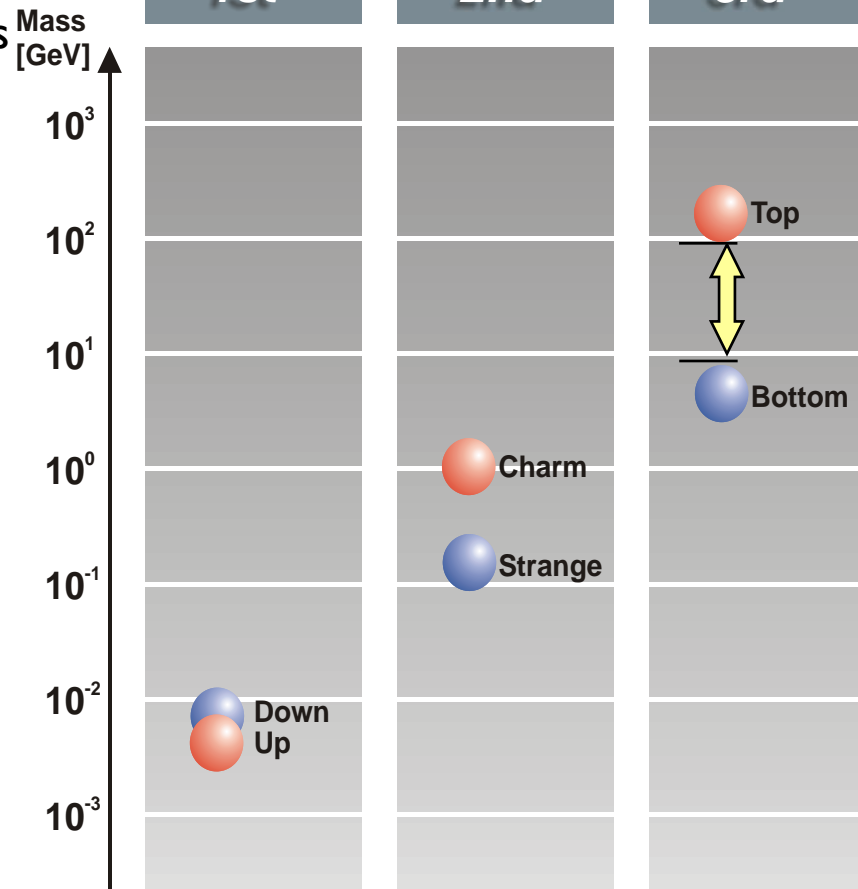
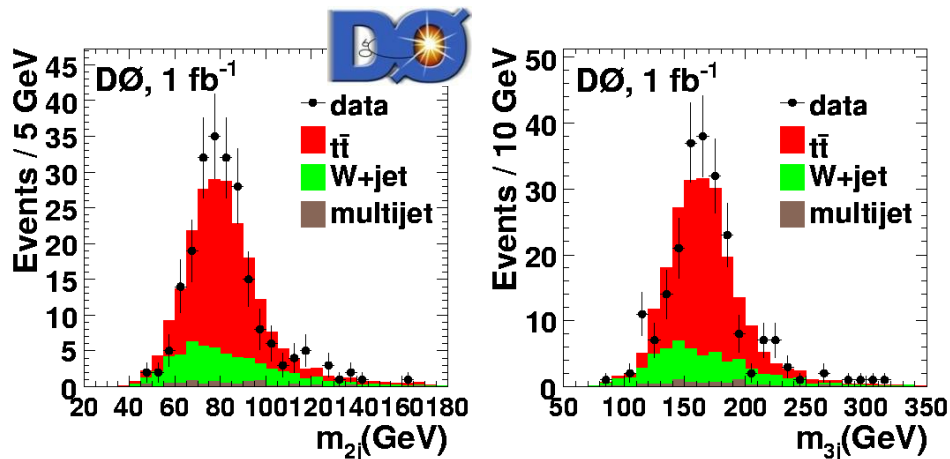


Selected Results

- ▶ Single top production
 - search, cross section ($|V_{tb}|$, anomalous coupling)
- ▶ Top pair production
 - cross section, $M(t\bar{t})$ differential cross section/spectrum
 - search for new physics ($t\bar{t}H$, t')
- ▶ Top decay
 - branching ratio, FCNC, rare decay
 - charged Higgs search
 - W -helicity (anomalous coupling)
- ▶ Top mass

Top Quark Mass

- Fundamental parameter of the SM
- Important ingredient for EW precision analyses
 - ⇒ incisive consistency checks
 - ⇒ constrain/rule out models
- Sophisticated techniques to minimize statistical and dominant systematic uncertainties (in-situ calibration of jet energy scale correction in $l+jets$ channel through hadronic M_W).



Top Quark Mass - Matrix Element Method

- The M.E. method is based on the calculation of event probability densities which are taken to be the sum of all contributing (and assumed to be non-interfering) processes. For example, in the case of two major processes:

$$P_{\text{evt}}(x; m_t) = f_{\text{top}} P_{\text{sig}}(x; m_t, JES) + (1 - f_{\text{top}}) P_{\text{bkg}}(x; JES)$$

- Probabilities are taken to be the differential cross sections for the process in question. For example, the signal probability is given by:

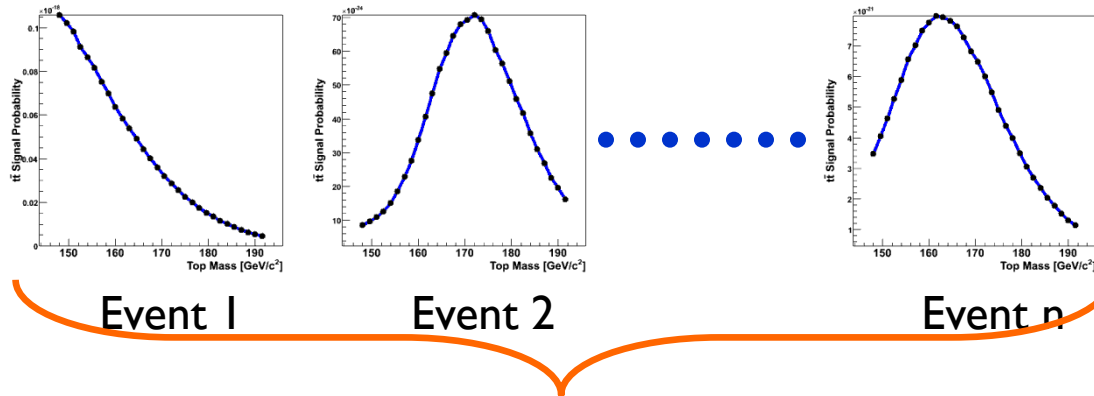
$$\begin{aligned} P_{\text{sig}}(x; m_{\text{top}}) &= \frac{d\sigma(x; m_{\text{top}})}{\sigma_{\text{obs}}(m_{\text{top}})} \\ &= \frac{1}{\sigma_{\text{obs}}(m_{\text{top}})} \times \int d\sigma(y) dq_1 dq_2 f(q_1) f(q_2) W(y, x) \end{aligned}$$

where:

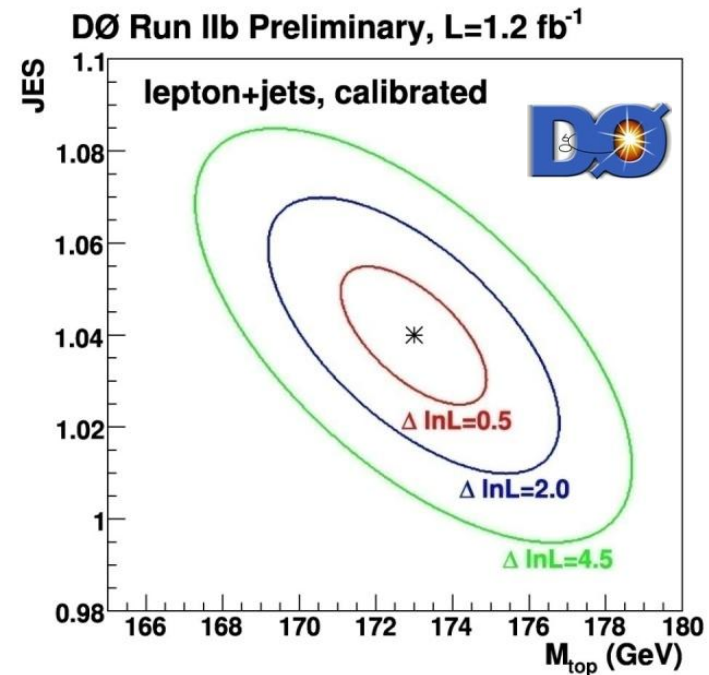
$$d\sigma = \frac{(2\pi)^4 |\mathbf{M}|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2)}} d\Phi_6$$

Top Quark Mass - Matrix Element Method

Probabilities are calculated for each individual event as a function of m_{top} (and JES):

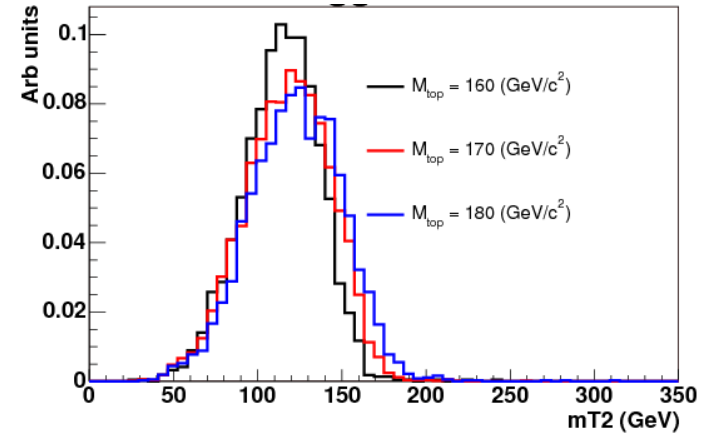
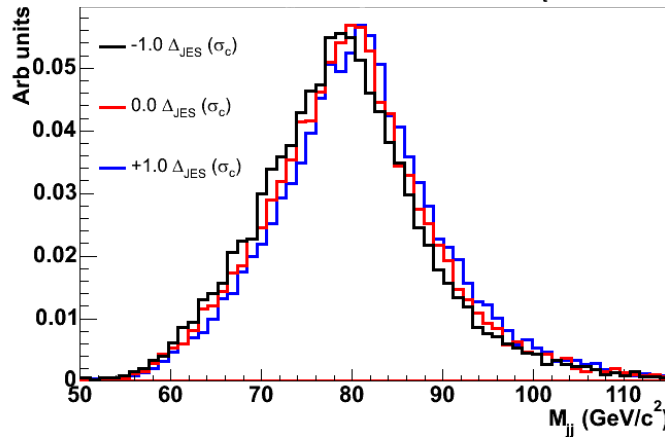
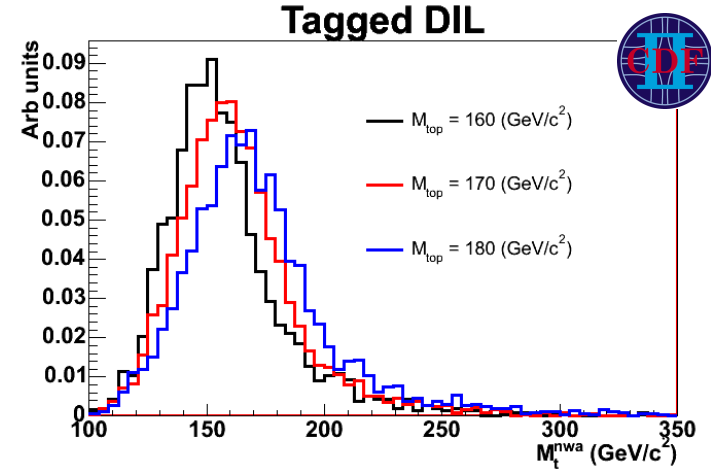
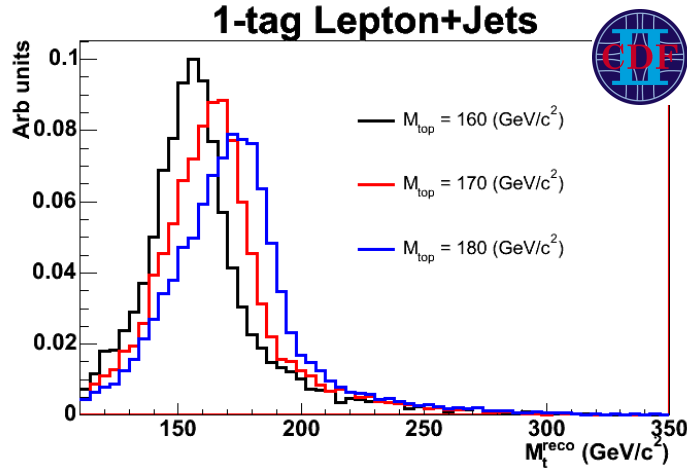


$$\mathcal{L}(x_1 \dots x_n; m_{top}) = \prod_{i=1}^n P(x_i; m_{top})$$



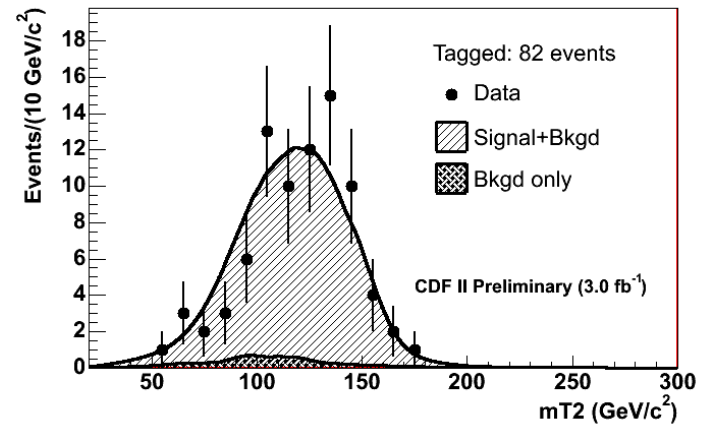
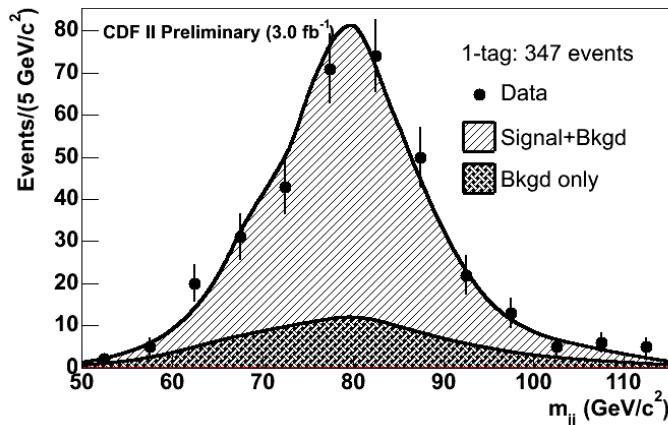
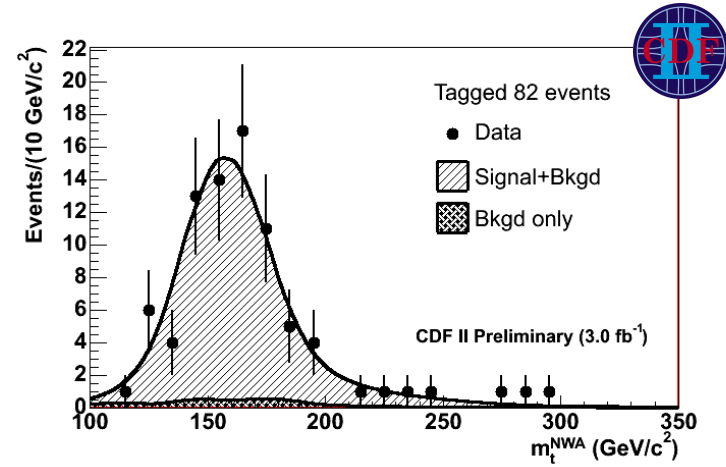
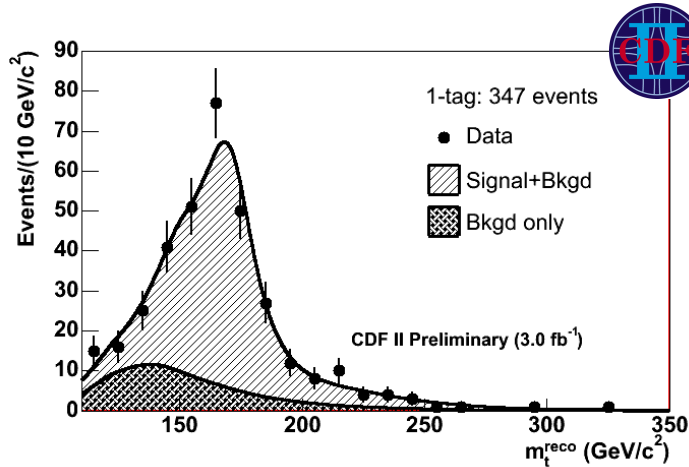
$$173.0 \pm 1.9(\text{stat+JES}) \pm 1.0(\text{syst}) \text{ GeV}$$

Top Quark Mass – Template Method



$$\mathcal{L}_k = \exp \left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2} \right) \times \prod_{i=1}^N \frac{n_s P_{sig}(m_i, y_i; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_i, y_i)}{n_s + n_b}$$

Top Quark Mass – Template Method



172.5 ± 1.6 (stat.+JES) ± 1.1 (syst) GeV/c²

169.0 ± 2.7 (stat.) ± 3.2 (syst) GeV/c²

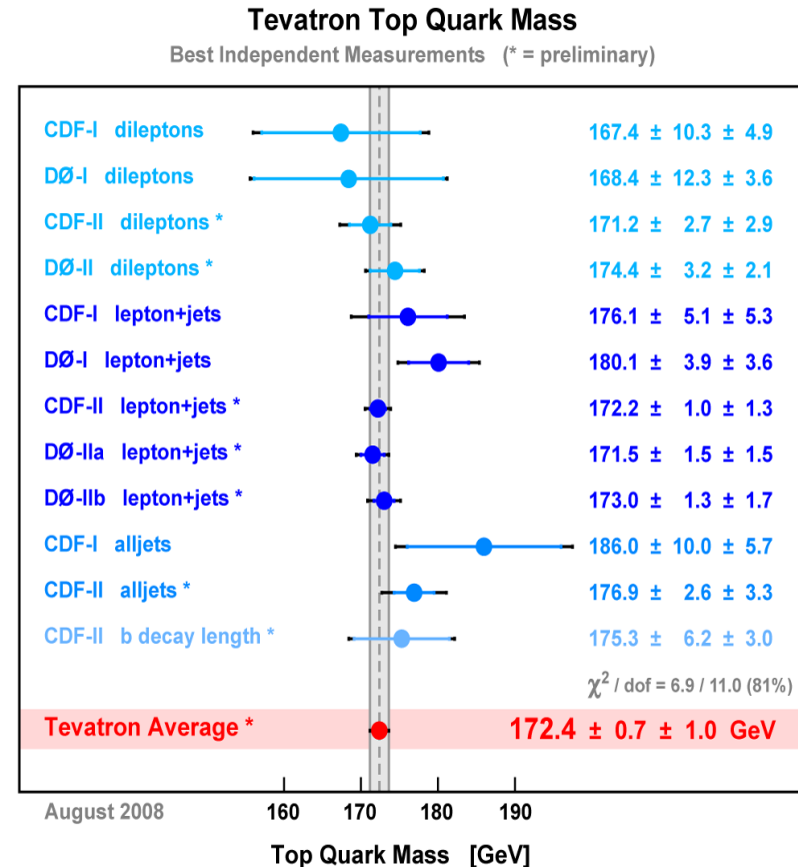
Combined: 171.8 ± 1.5 (stat.+JES) ± 1.1 (syst) GeV/c²

Top Quark Mass – Direct Measurements

- Fundamental parameter of the SM
- Important ingredient for EW precision analyses
 \Rightarrow incisive consistency checks
 \Rightarrow constrain/rule out models
- Sophisticated techniques to minimize statistical and dominant systematic uncertainties.
- Current world-average (most sensitive channels use up to 2.7 fb^{-1}):

$$m_t = 172.4 \pm 0.7(\text{stat}) \pm 1.0(\text{syst}) \text{ GeV}$$

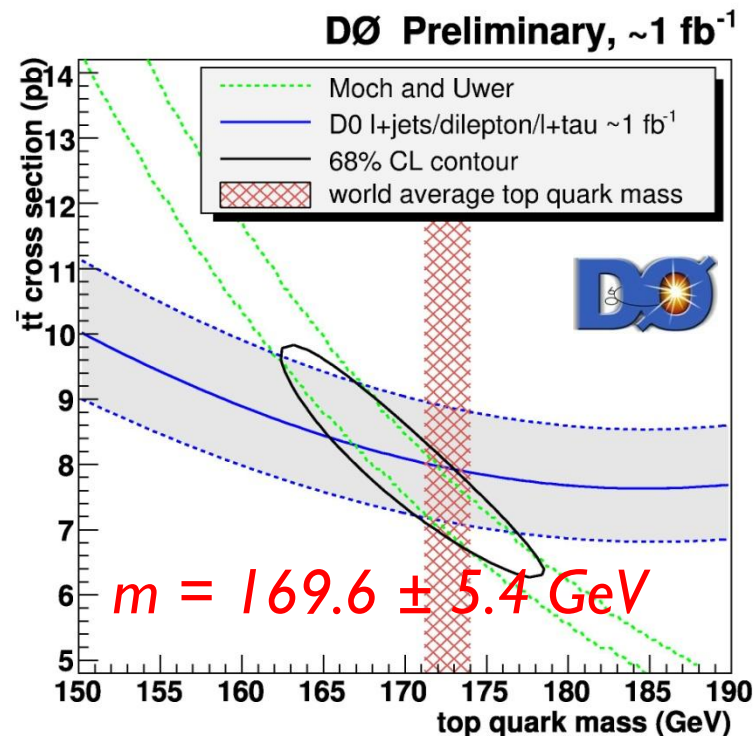
Measurements are limited by systematic uncertainties (signal modeling, b-jet response).



Top Quark Mass - From Cross Section

Assuming SM production, top mass can be extracted by comparing measured to calculated cross sections

- mass is measured in a well-defined renormalization scheme
- systematic largely uncorrelated with other methods



Summary

- ▶ A broad and exciting Top physics program on-going at the Tevatron.
- ▶ Many new results, consistent with SM.
 - ▶ More results at
<http://www-cdf.fnal.gov/physics/new/top/top.html>
http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
- ▶ Keep trying to improve sensitivity and precision.